



SCIENCE AT FERMILAB (AND BEYOND!)

Dan Hooper – Fermilab
Saturday Morning Physics

What is Physics?

Physics is hard to define. Here are some definitions that I found in online dictionaries:

- “The science that deals with matter, energy, motion, and force.”
- “A science that deals with matter and energy and their interactions”
- “The branch of science concerned with the nature and properties of matter and energy. The subject matter of physics, distinguished from that of chemistry and biology, includes mechanics, heat, light and other radiation, sound, electricity, magnetism, and the structure of atoms.”

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In my opinion, these definitions are not “wrong”, but if you think about it closely, they are not very useful.

- Everything in the universe is made up of matter and energy.
- Everything that happens can be described in terms of motion and interaction
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A more useful definition, I would argue, is that physics is the branch of science that strives to address the most *fundamental* of questions about our universe.



Physics

Physics



Chemistry

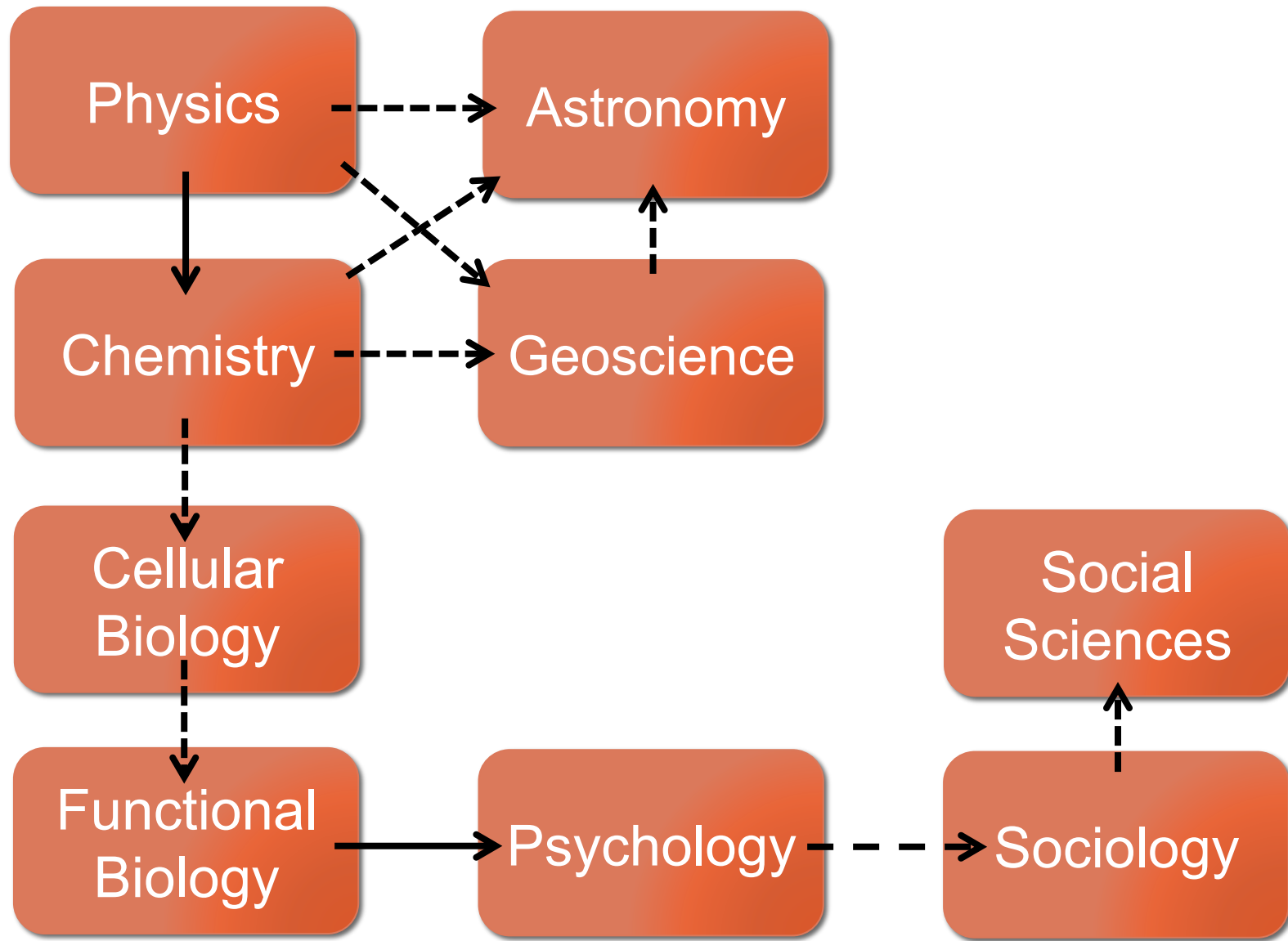
Physics



Chemistry



Cellular
Biology



What is Physics In Practice?

The physics that you are most likely learn in high school, or in a first year college course, will cover topics such as:

- Force and motion (17th century)
- Gravity (17th century)
- Electromagnetism (18th and 19th centuries)
- Thermodynamics (19th century)
- Wave phenomena (19th century)

In the twentieth century, physics changed dramatically, with the discovery of Einstein's theory of relativity and quantum physics.

In practice, all physicists are trained in each of these areas, and we put them to use on a regular basis. But we are not generally studying any of these topics, per se.

Some Areas of Current Investigation in Physics

Particle Physics

- What forms can matter and energy take in our universe? How do they fit together into a more complete and predictive theory?
- Why do some particles have mass? What causes them to?
- What is the “dark matter”?
- What is gravity at a quantum level?

Some Areas of Current Investigation in Physics

Condensed Matter Physics (Solid State Physics)

- What causes high-temperature superconductivity?
- Many aspects of turbulence remain a mystery
- Do the equations that we use to describe fluid flow have solutions that apply in all conditions? Or do they break down?

Some Areas of Current Investigation in Physics

Cosmology

- How did the Big Bang take place?
- Will the universe expand forever, or not?
- Are there really three dimensions of space? If so, why?
- What is the geometry of the universe?
- Why does time flow forward in one direction and backward in another?
- What is “dark energy”?
- Did the universe undergo a period of ultrafast expansion (inflation)? If so, why and how?



From The Fermilab Website:

“What are we made of? How did the universe begin? What secrets do the smallest, most elemental particles of matter hold, and how can they help us understand the intricacies of space and time?

Since 1967, Fermilab has worked to answer these and other fundamental questions and enhance our understanding of everything we see around us. As the United States' premier particle physics laboratory, we do science that matters. We work on the world's most advanced particle accelerators and dig down to the smallest building blocks of matter. We also probe the farthest reaches of the universe, seeking out the nature of dark matter and dark energy.”

Early Attempts Toward Particle Physics

Many philosophers throughout history have contemplated the nature of matter

Some of the ancient Greeks advocated for:

- Everything is made up of a finite number of “atoms”
(Democritus, Lucretius, 440 BCE)
- Everything is made up of combinations of “elements”, such as air, earth, fire, water
(Plato, Aristotle, among others, 360-350 BCE)

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The work of these ancient philosophers is often presented as constituting the beginning of science.

They were *not*, however, applying the scientific method in any consistent way.

They were speculating about the same topics we now address scientifically, but were not really doing science.

The Establishment of Chemistry

Throughout the 18th and 19th centuries, a great deal of progress was made in identifying the properties of various chemical elements:

- Hydrogen (1766), Oxygen (1773), etc.
- In 1808, John Dalton proposed the first modern atomic theory
- In 1869, Dmitri Mendeleev published the first modern periodic table (containing 66 elements at the time)

During this period of time, chemistry was established as a science, but there remained little understanding of what “atoms” really were



The Beginning of Particle Physics

Around the beginning of the 20th century, we began to discover the nature of atoms... and the quantum nature of matter

The Beginning of Particle Physics

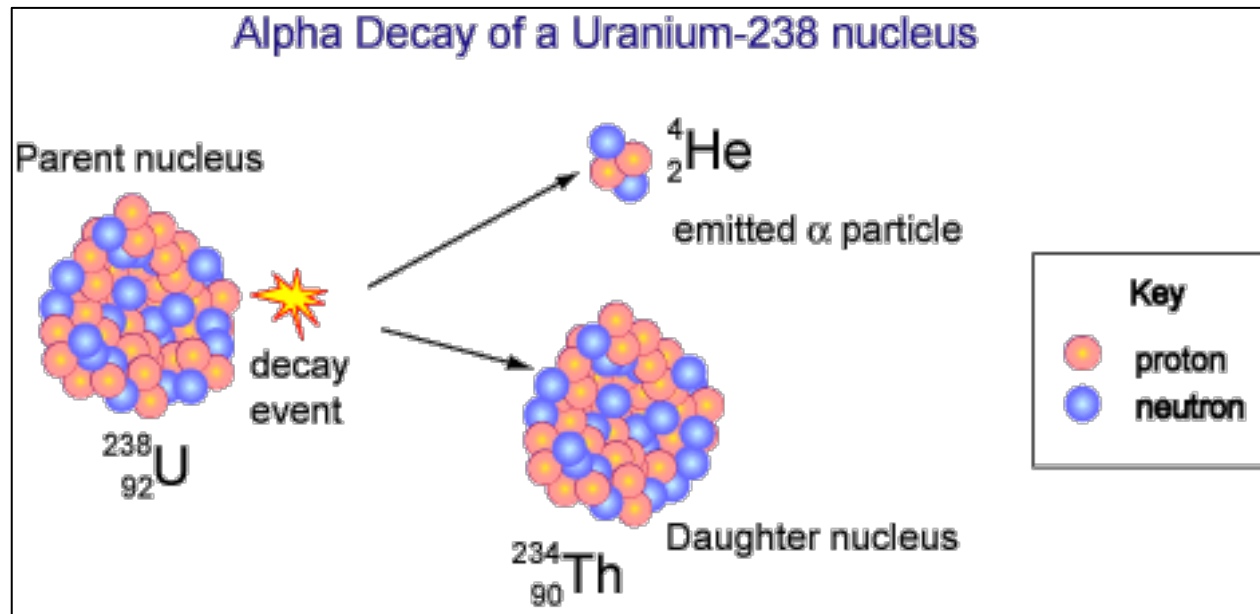
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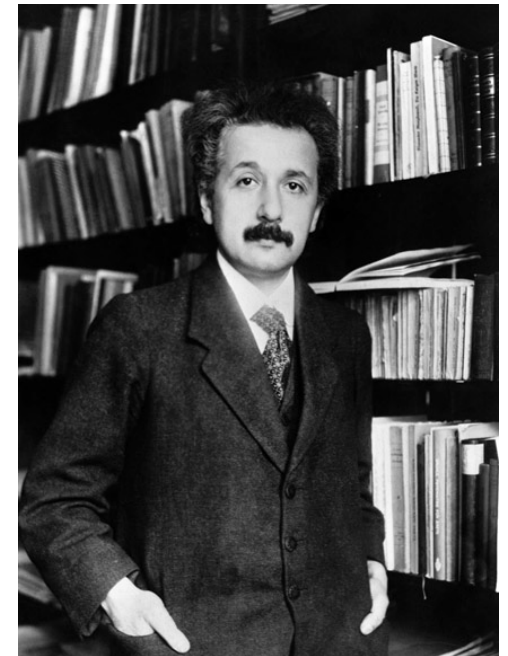
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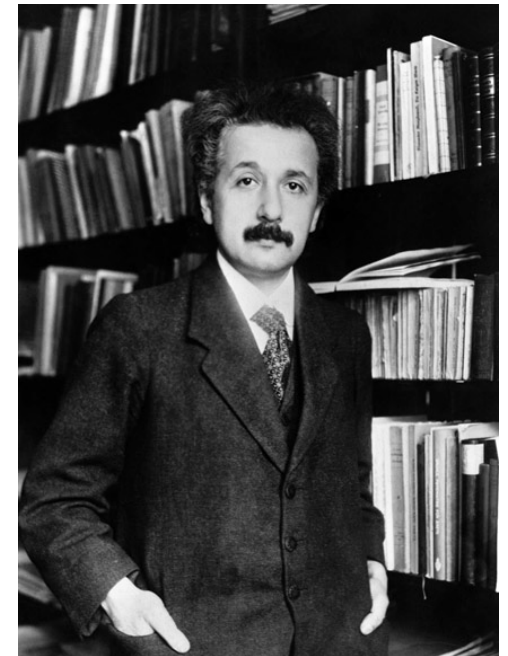
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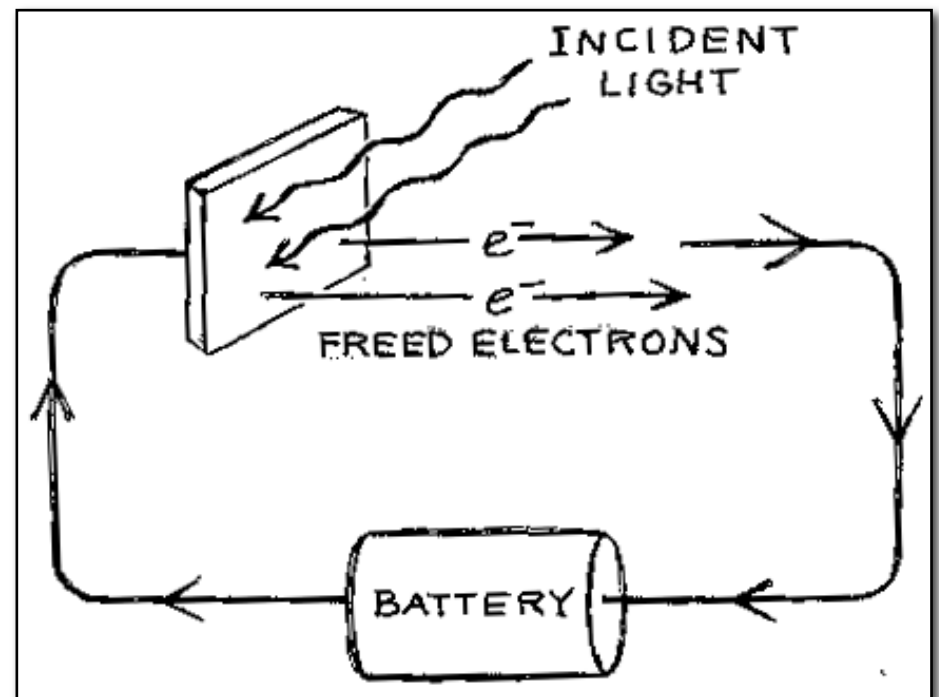
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Einstein and the Quantum Mechanics Revolution

Prior to 1905, physicists thought of light as waves of electromagnetic radiation, but in this view, it was difficult to explain what was known as the photoelectric effect:

- Light is directed at a metal plate hooked up to a battery; without any light, no current flows
- Once the light hits the plate, it was expected that electrons would be freed from the metal, and electric current would begin to flow around the circuit
- When tested, it was found that only high frequency light caused an electric current



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Einstein proposed that light waves were made up of individual pieces – called “quanta” (now called photons) - each with an amount of energy proportional to their frequency

- Low frequency light was made up of low energy photons that could not free electrons from the metal plate, and thus could not generate electric current (no matter how many)
- High frequency light, in contrast, was made up of photons with more energy, which could free electrons, creating current

Einstein's interpretation meant that **light was both a wave, *and* was made up of particles**

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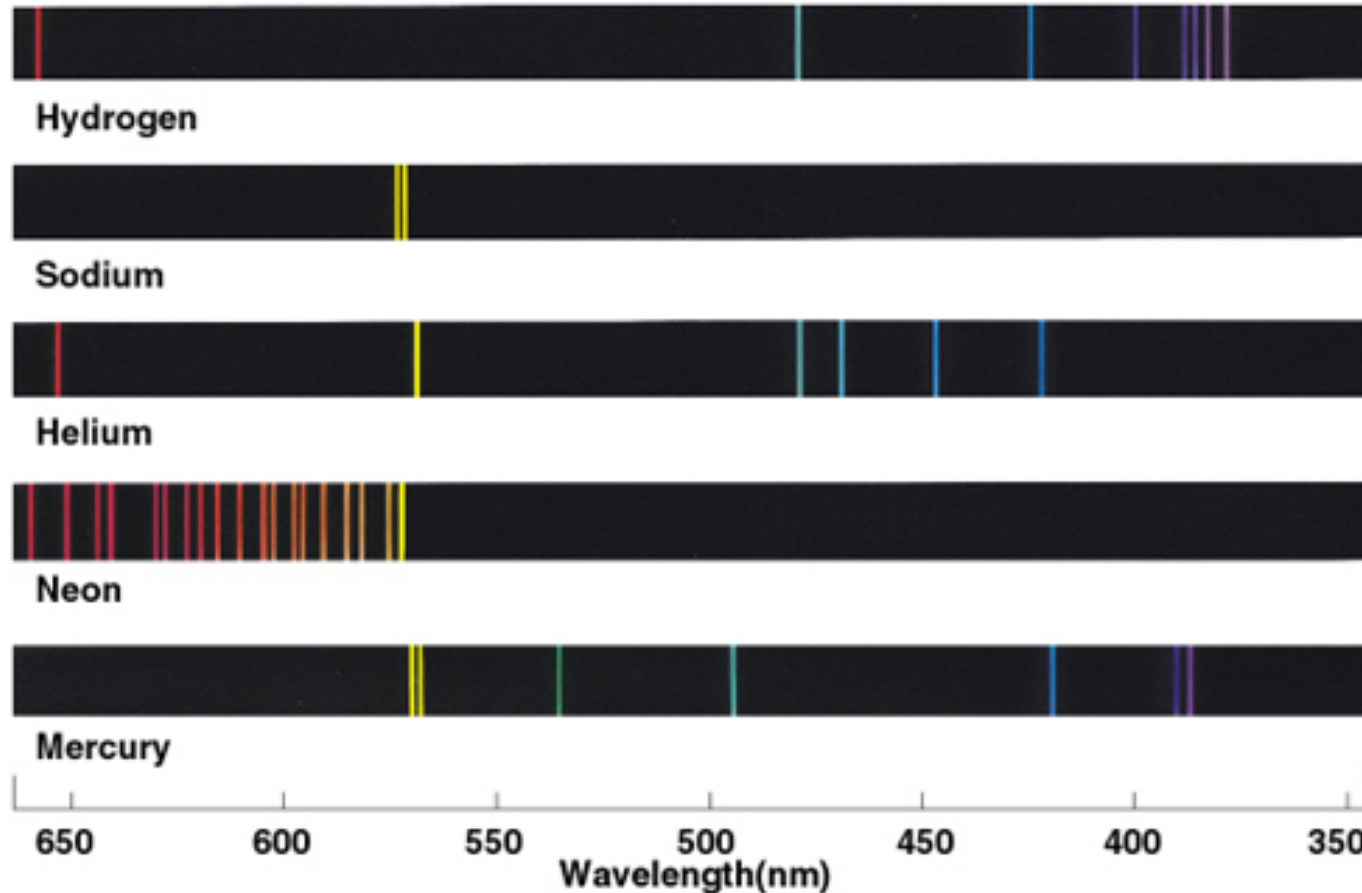
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- Niels Bohr uses early concepts of quantum mechanics to explain observed properties of the hydrogen atom – treating electrons as waves! (1913)

Bohr and the Quantum Mechanics Revolution

During the same period of time, various chemical elements had been observed to radiate light at different, discrete, wavelengths

Heated objects were also observed to radiate a continuous spectrum of light

In both cases, physicists were unable to explain what they were measuring

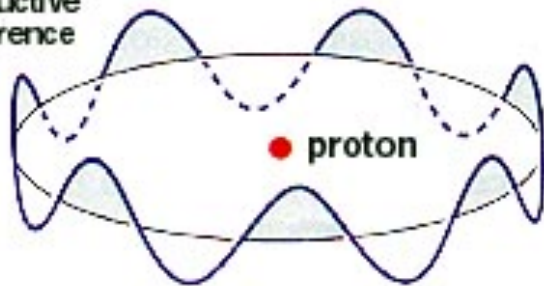


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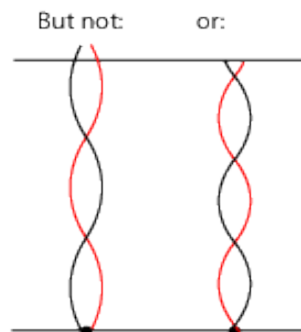
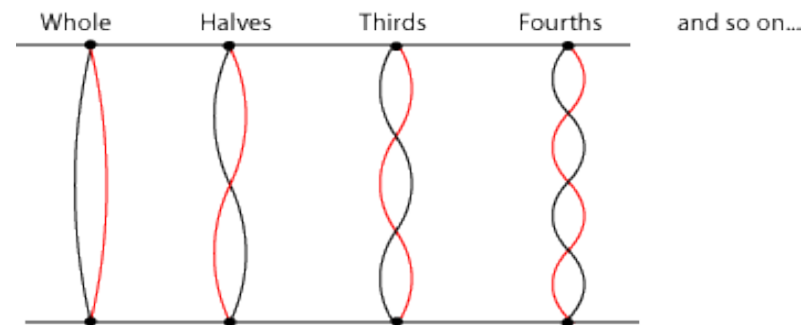
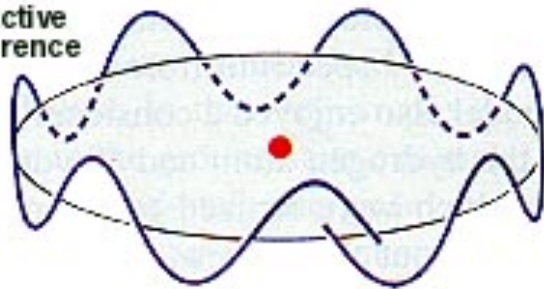
Standing waves (those with an integer number of wavelengths around the atom) are the configurations that can exist

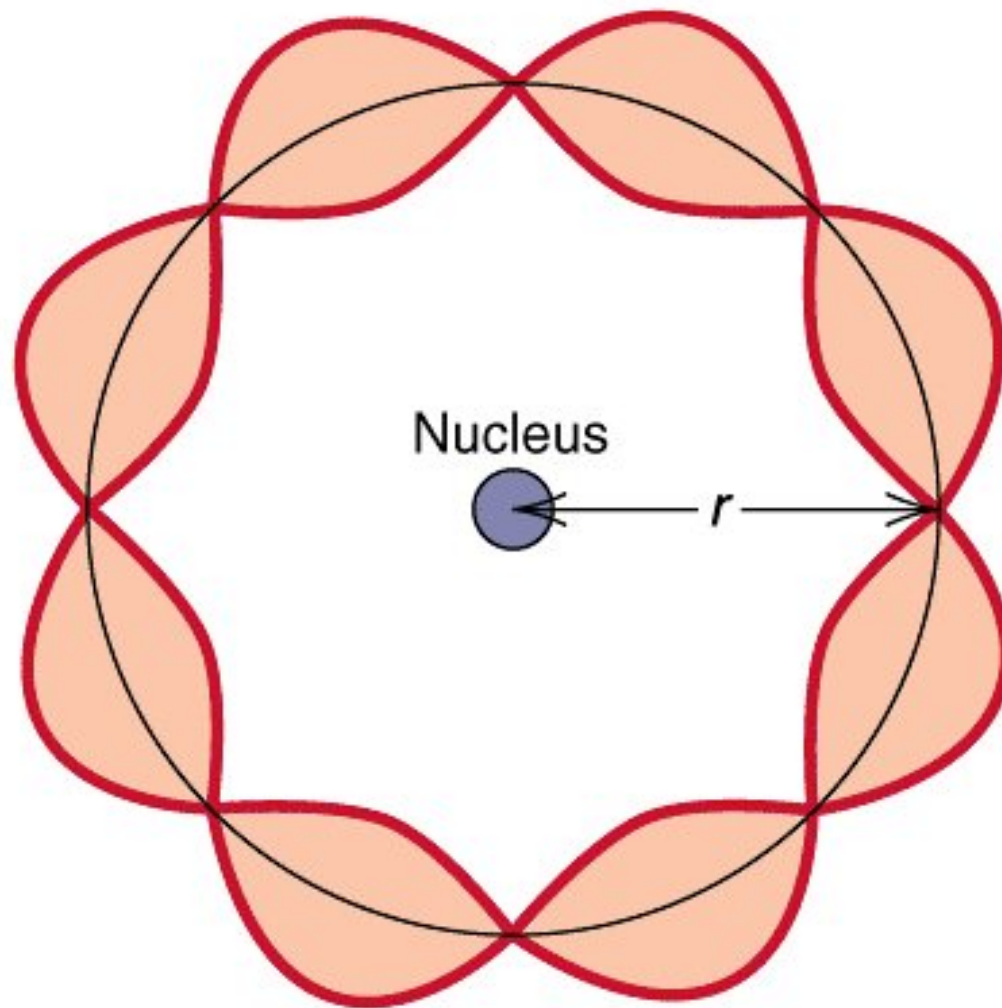
This is just like standing wave patterns on a vibrating string

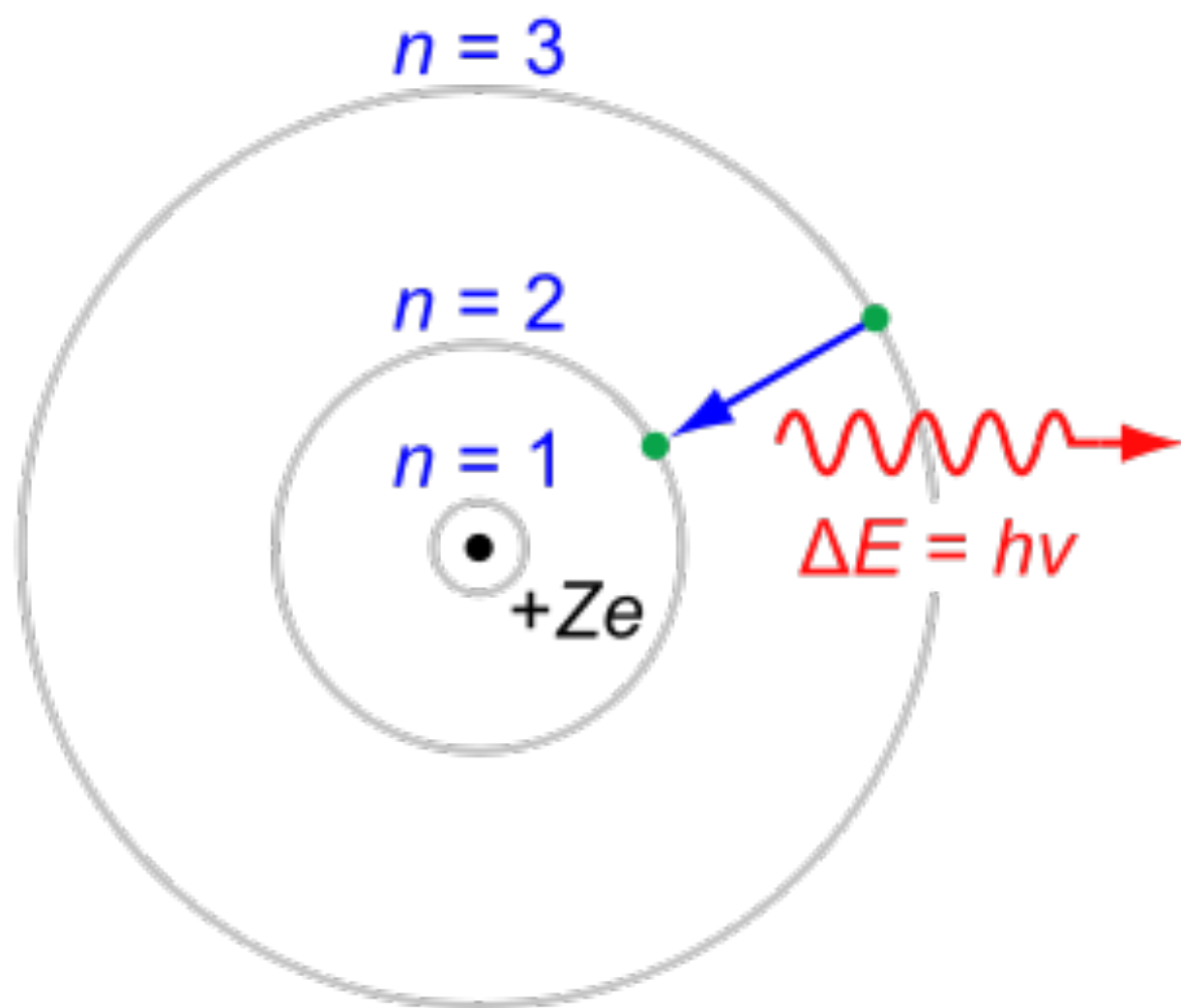
Constructive interference

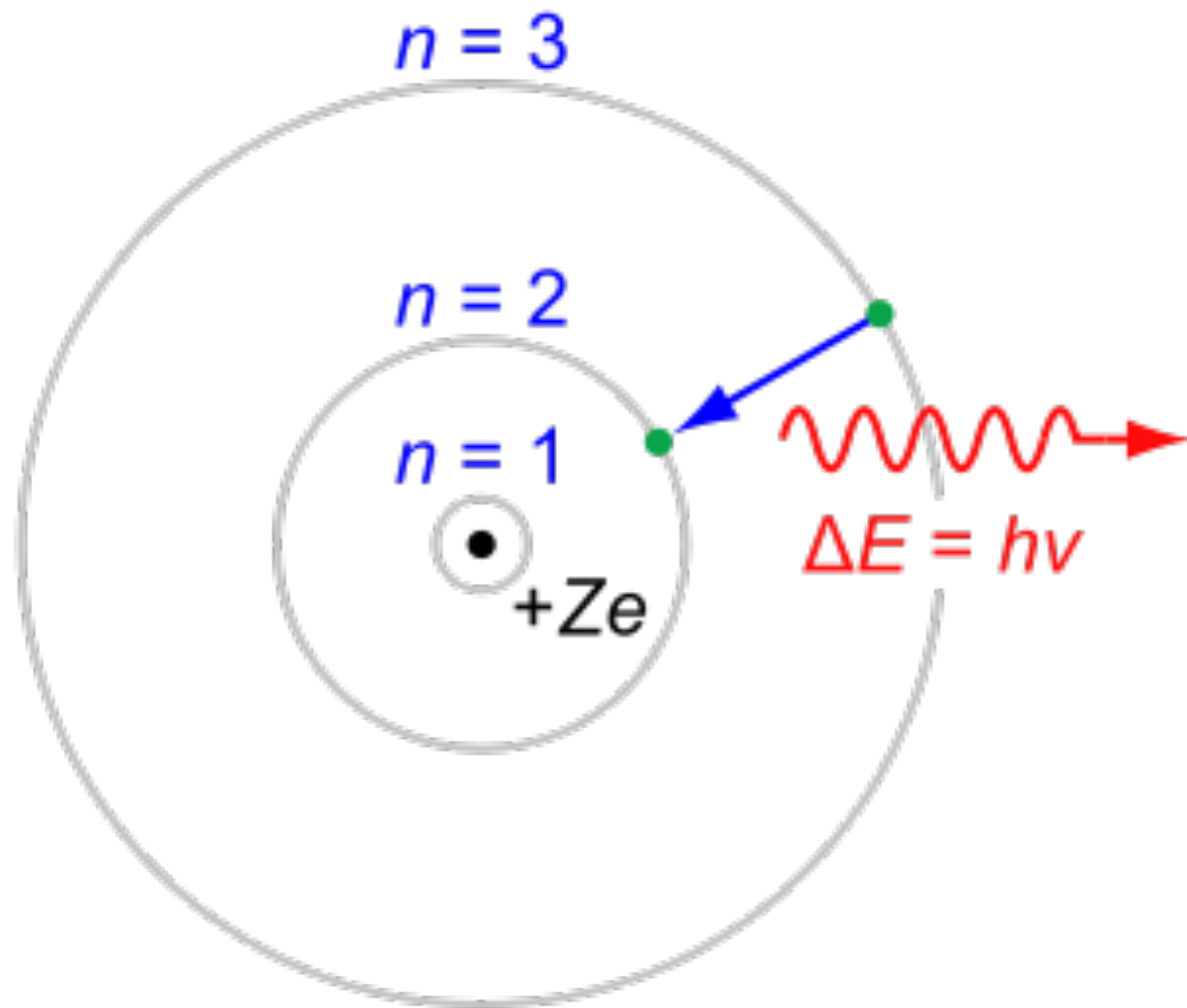


Destructive interference









“Quantized” Energy Levels!

This means that electrons are **not only particles, but also waves!**

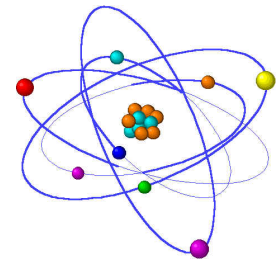
Everything is a Particle and Everything is a Wave

Throughout the twentieth century, experiments have revealed to us over and over again that all matter is made up of discrete pieces (particles) that individually behave like waves

When we talk about the field of “particle physics”, we are talking about the study of these particle-waves that make up everything in our universe

We don't notice the wave-like nature of matter in the macroscopic world
(A 100 kg person walking at 1 m/s has a wavelength of $\lambda \sim 6 \times 10^{-36}$ m)

But on atomic and sub-atomic scales, our world is fully particle and fully wave
(An electron moving around an atom has a wavelength of $\lambda \sim 10^{-10}$ m, which is about the size of a typical atom)



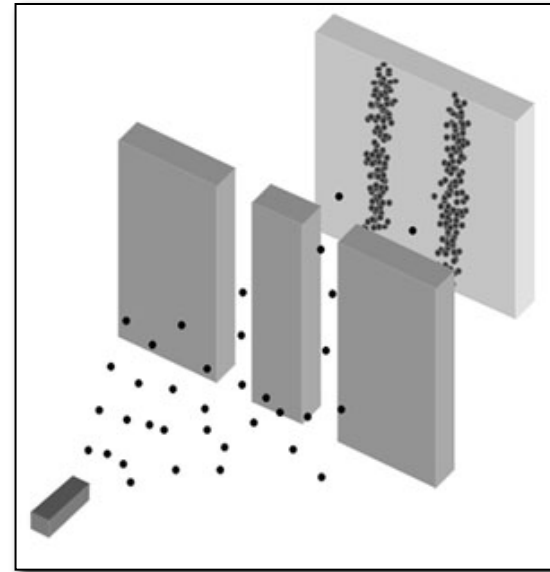
But What is “Waving”?

- Water waves are made up of water molecules; peaks of the waves are where there is the most water
- Sound waves are made up of atoms/molecules in high pressure and low pressure patterns
- Waves on a string are the motion of atoms/molecules

Question: If photons and electrons (and other quantum particles) are waves, *what is waving?*

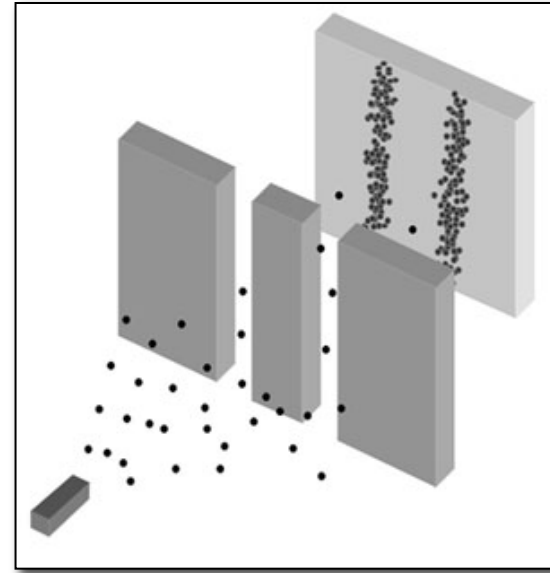
The Double Slit Experiment

If we shoot (non-wavelike) particles through two slits in a barrier, and watch how they accumulate on a far surface, we will find the following:

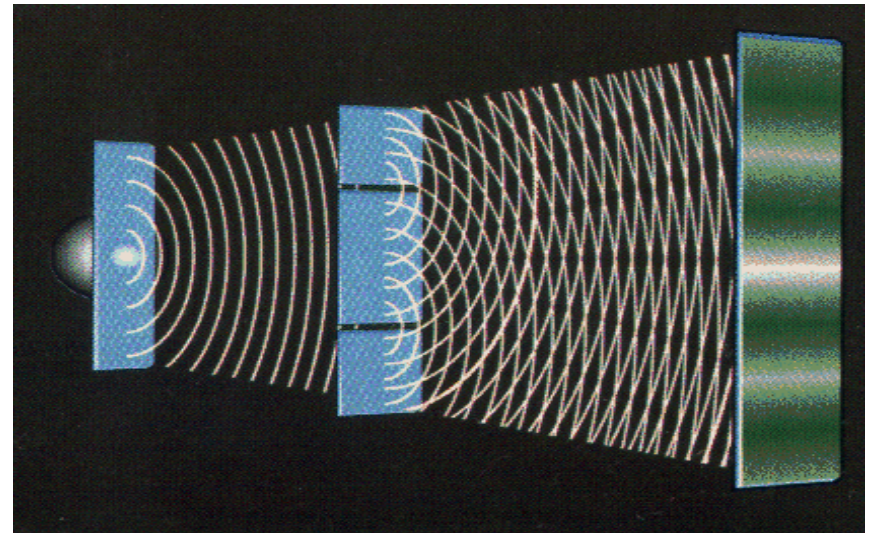


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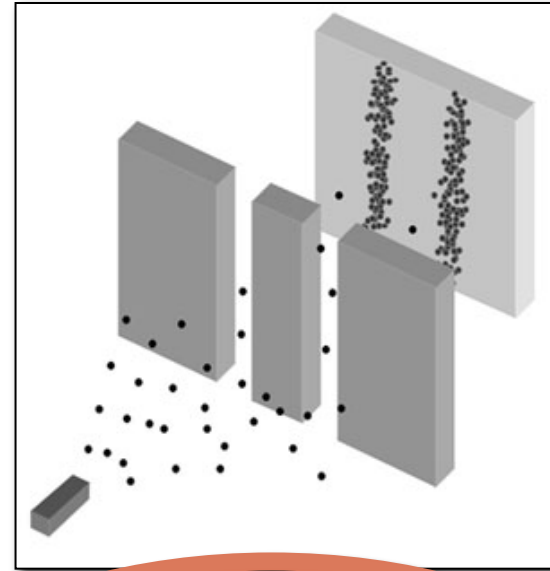


But if we projected waves through the same apparatus, we will observe an interference pattern:

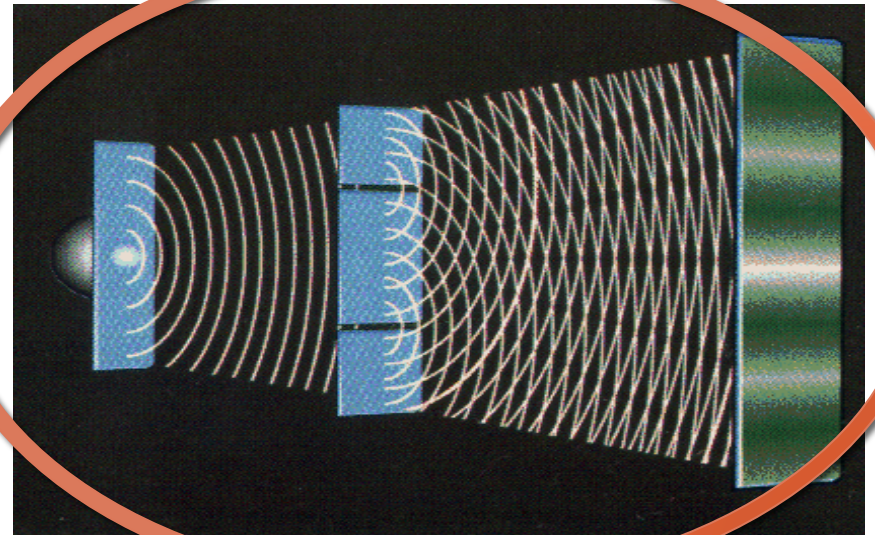


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The Moral of the Experiment: Even Individual Particles Behave Like Waves

Unlike waves made of sound, water, sound, or on a string, quantum particle-waves cannot be described as patterns among a large number of molecules

Instead, we have to think of quantum particle-waves are patterns of *probability*

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Instead, we have to think of quantum particle-waves are patterns of *probability*

Particles are not, generally speaking, at one place at one time, nor are they moving with a singular velocity, or possess a singular quantity of energy

Events do not even happen at precisely one time

Many kinds of events that are impossible in classical physics are possible in quantum physics

All of these quantities are described *probabilistically* according to the laws of quantum mechanics

From Quantum Mechanics to Particle Physics

While quantum mechanics was being discovered and understood, the only known particles were the electron (1897), the photon (1905), the proton (1919), and the neutron (1932)

There was nothing known at the time about these particles that gave us any insight into why they existed, or why they have the properties that they do. The equations of quantum mechanics told us how these particles would behave, but we had no larger theory – no big picture – for why our universe is the way it is

(similar to how early chemistry was a taxonomy of unrelated substances, without any larger understanding of their interconnection)

The Data!

A string of new particle discoveries (the most important):

Positron, e^+ – 1932

Muon, μ^\pm – 1937

Pion, π^0, π^\pm – 1947

Kaon, K^0, K^\pm – 1947

Lambda, Λ^0, Λ^\pm – 1947

Antiproton, \bar{p} – 1955

Electron anti-neutrino, $\bar{\nu}_e$ – 1956

Muon neutrino, ν_μ – 1962

Xi, Ξ^0, Ξ^\pm – 1964

J/ Ψ – 1974

Tau, τ^\pm – 1975

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Z and W bosons, Z^0, W^\pm – 1983

Top quark, t – 1995 (at Fermilab!)

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And not only particle discoveries,
but also detailed measurements of
their properties:

-mass

-spin

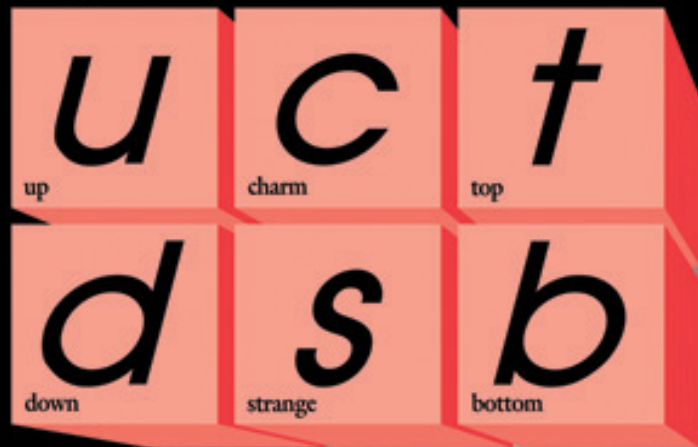
-interactions with other particles

For example, the “magnetic moment”
of the electron:

$$g_e = 2.00231930436170 \pm 0.000000000000152$$

***This is the more precisely
measured quantity in the history
of humankind!***

Quarks



Forces



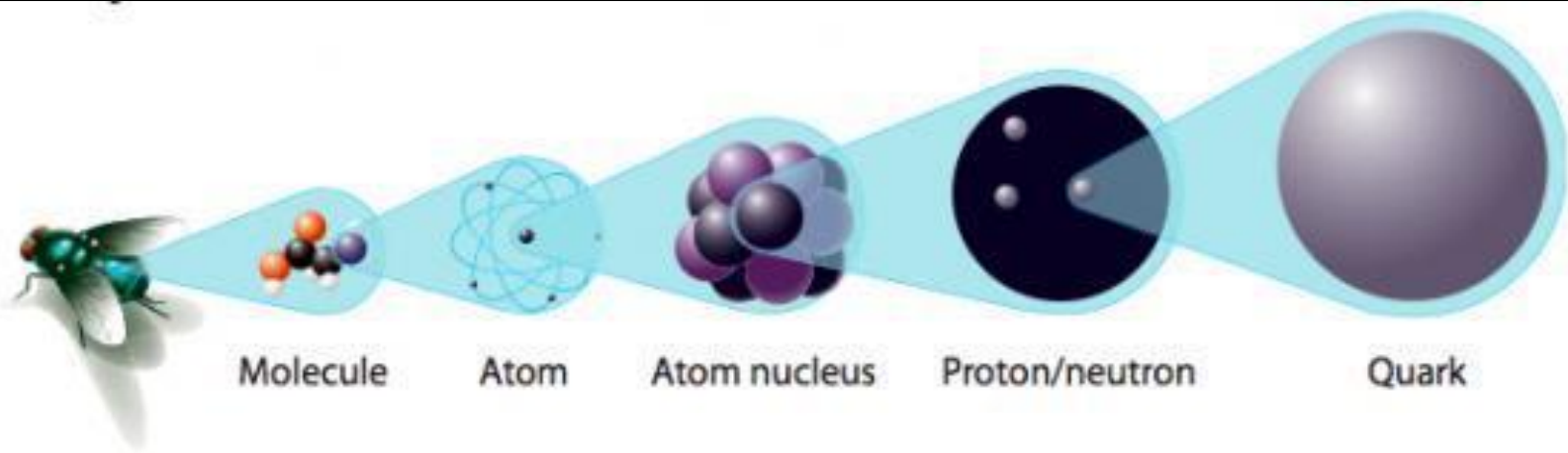
Leptons

Baryons

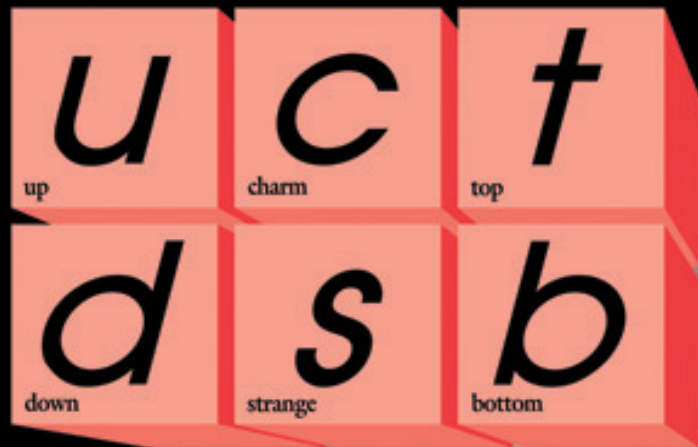
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
p	proton	uud	1	0.938	1/2
\bar{p}	antiproton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2

Mesons

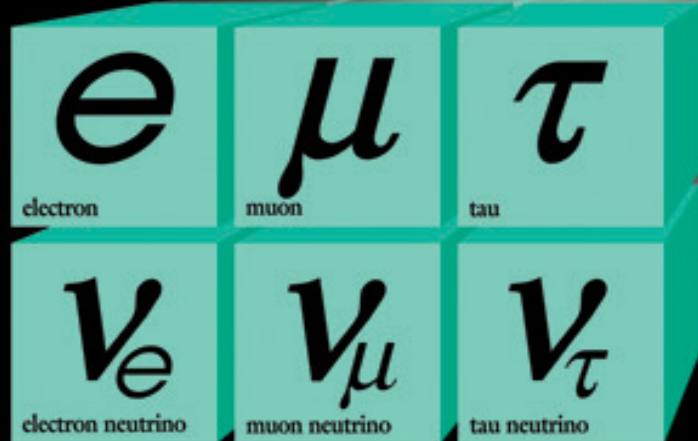
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0



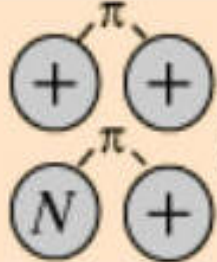
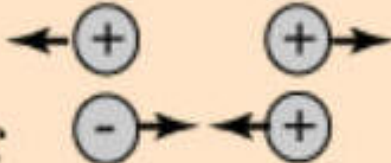

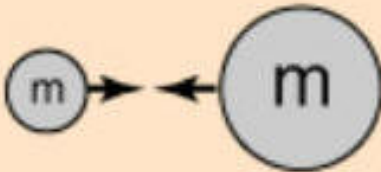
Quarks

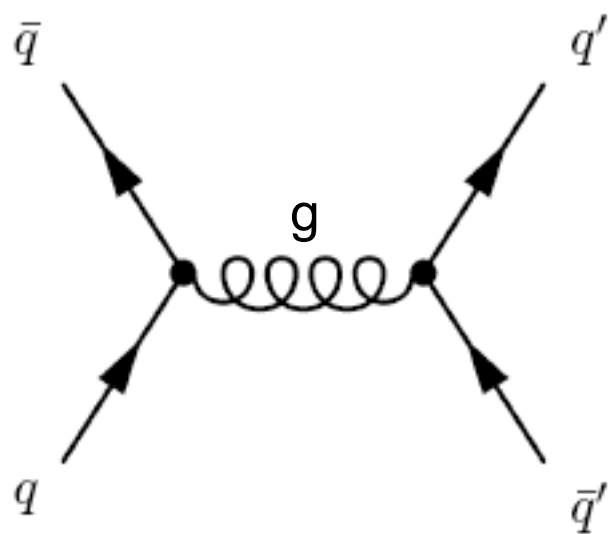
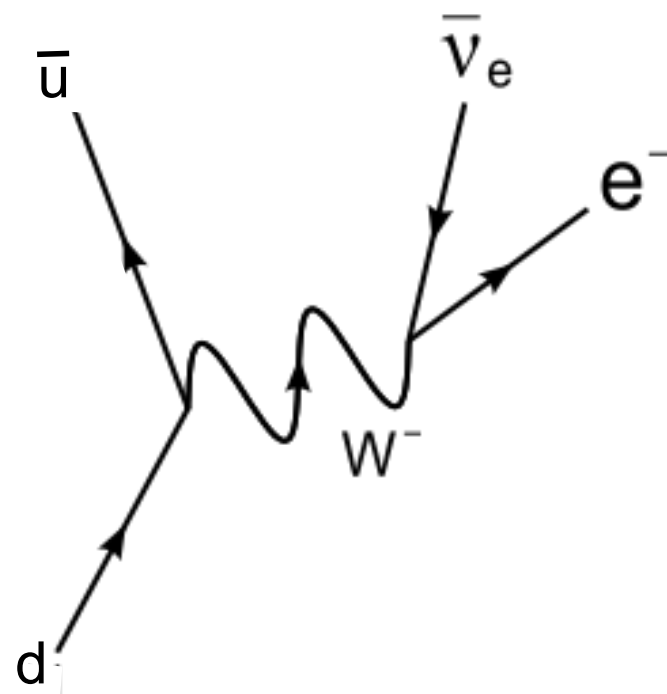
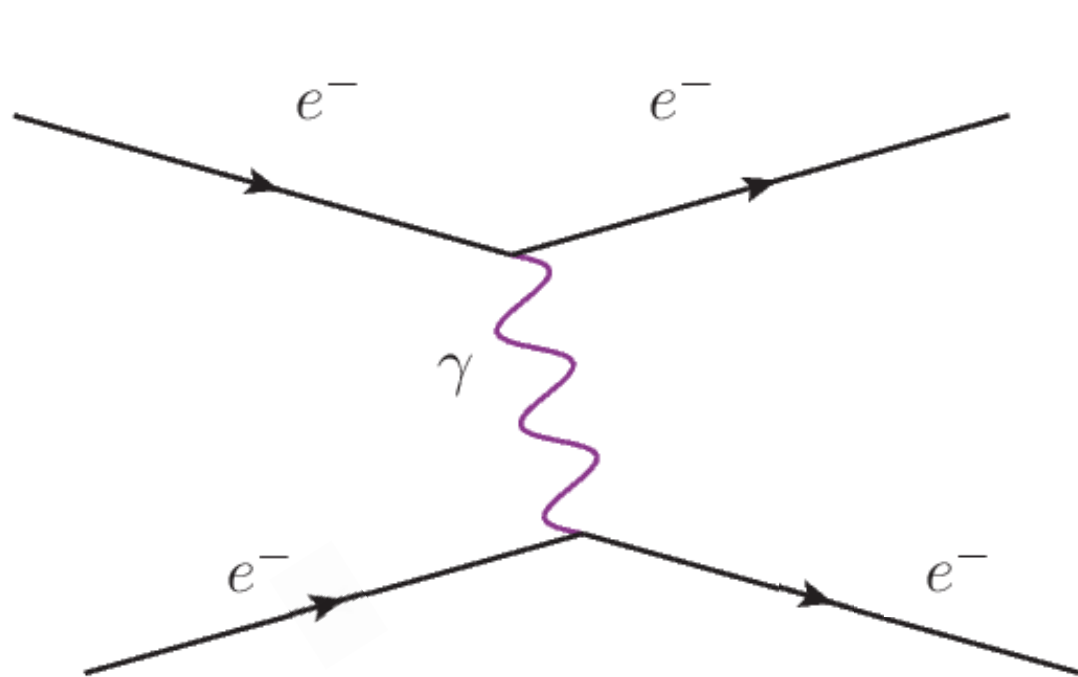


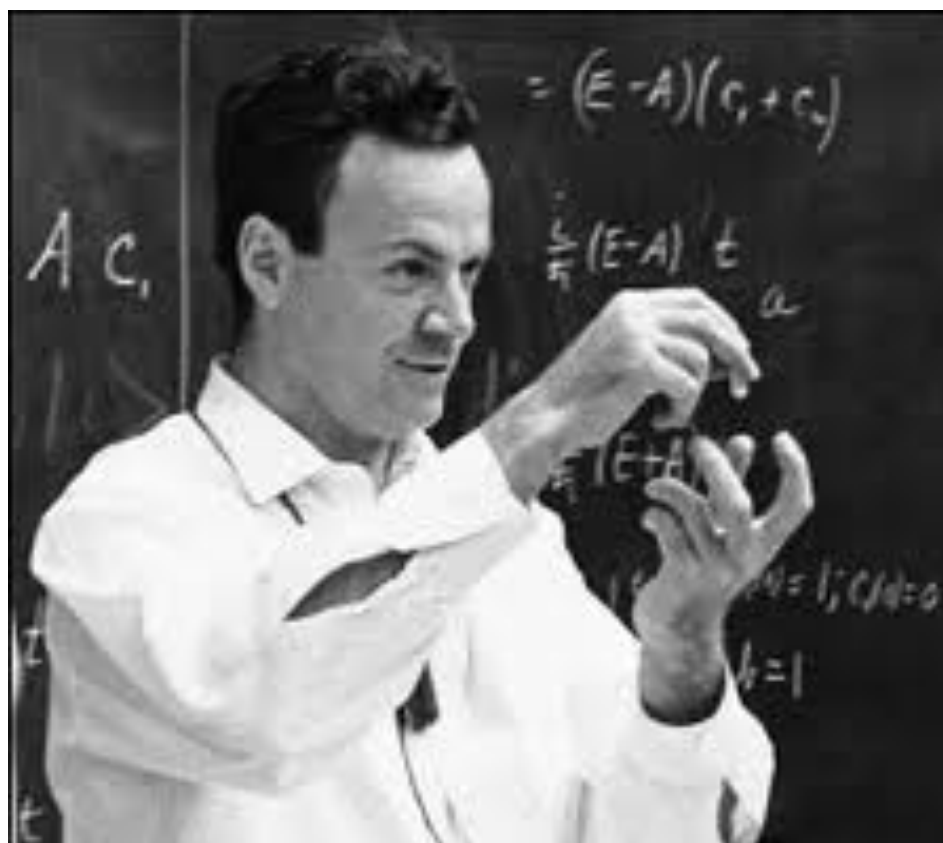
Forces

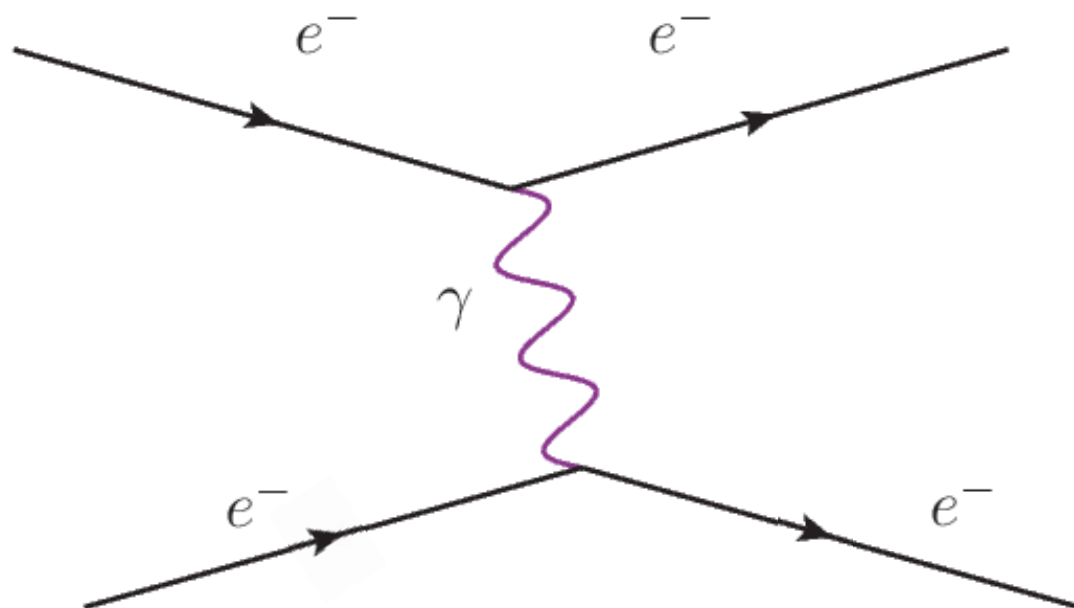


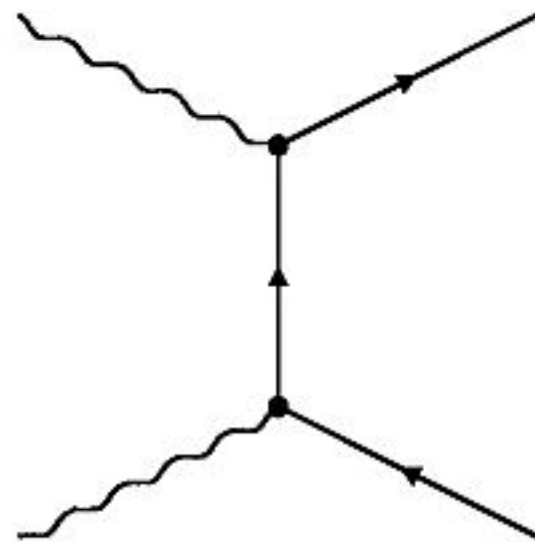
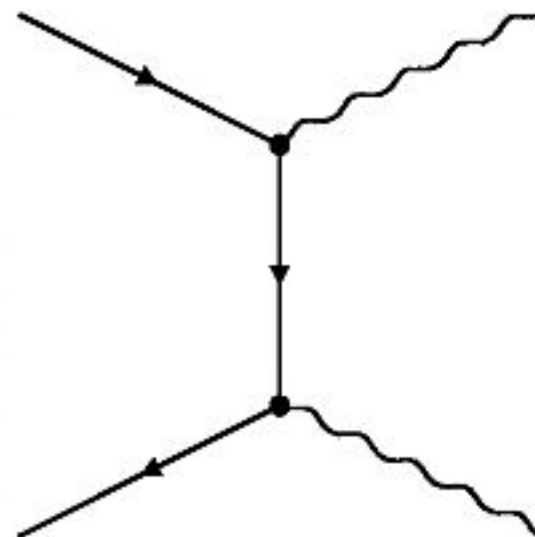
Leptons

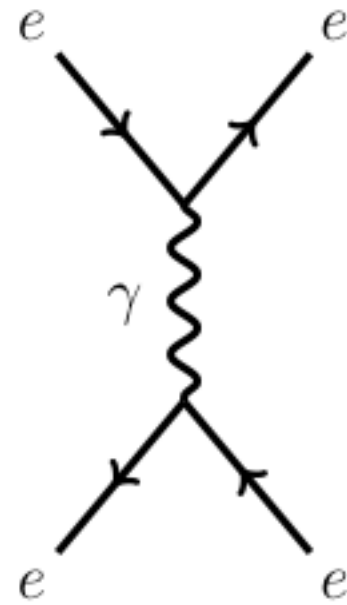
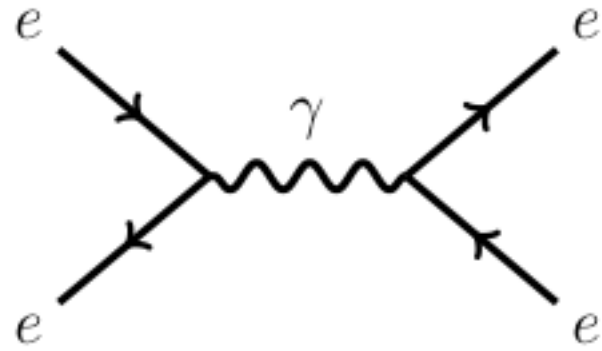
<i>Strong</i>	 <p>Force which holds nucleus together</p>	Strength 1	Range (m) 10^{-15} (diameter of a medium sized nucleus)
<i>Electro-magnetic</i>		Strength $\frac{1}{137}$	Range (m) Infinite
<i>Weak</i>	 <p>neutrino interaction induces beta decay</p>	Strength 10^{-6}	Range (m) 10^{-18} (0.1% of the diameter of a proton)
<i>Gravity</i>		Strength 6×10^{-39}	Range (m) Infinite

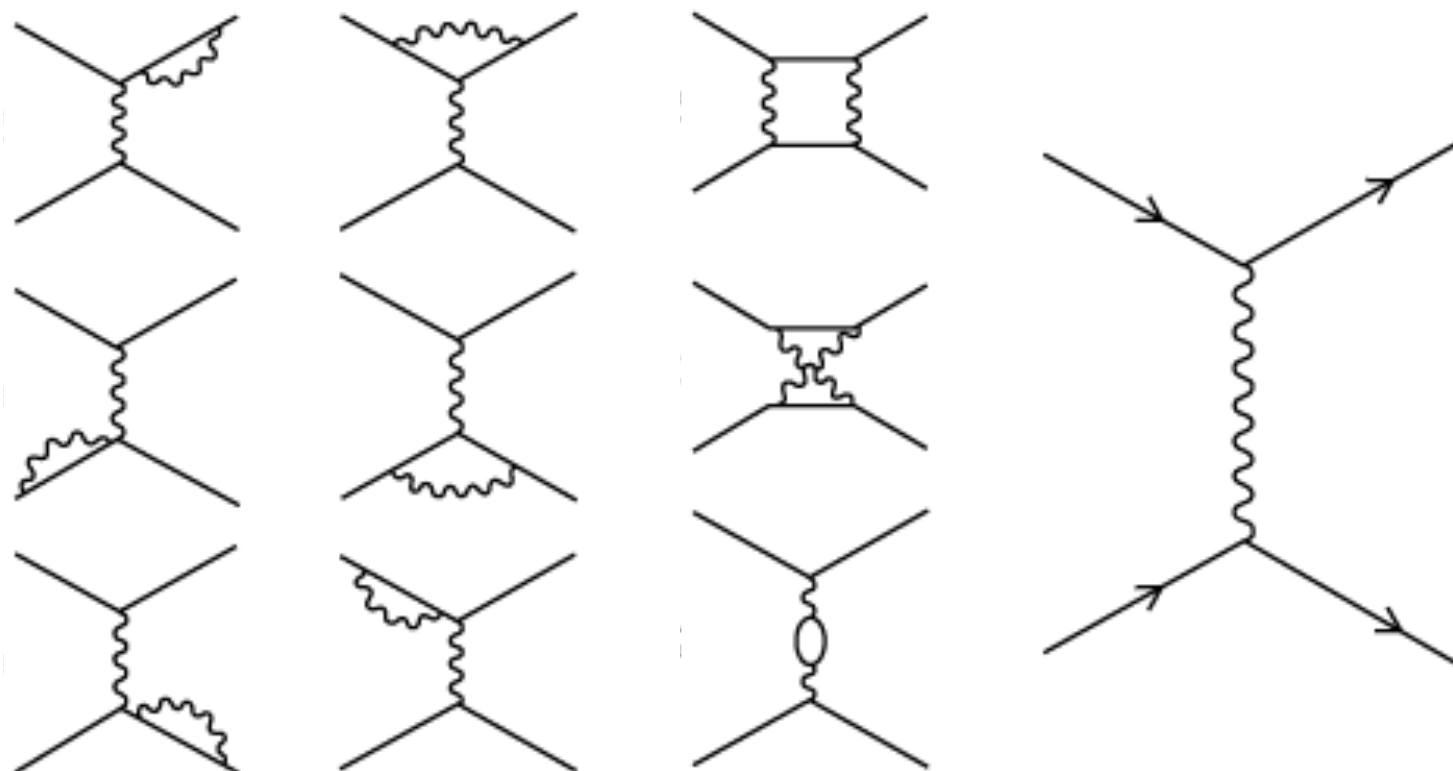


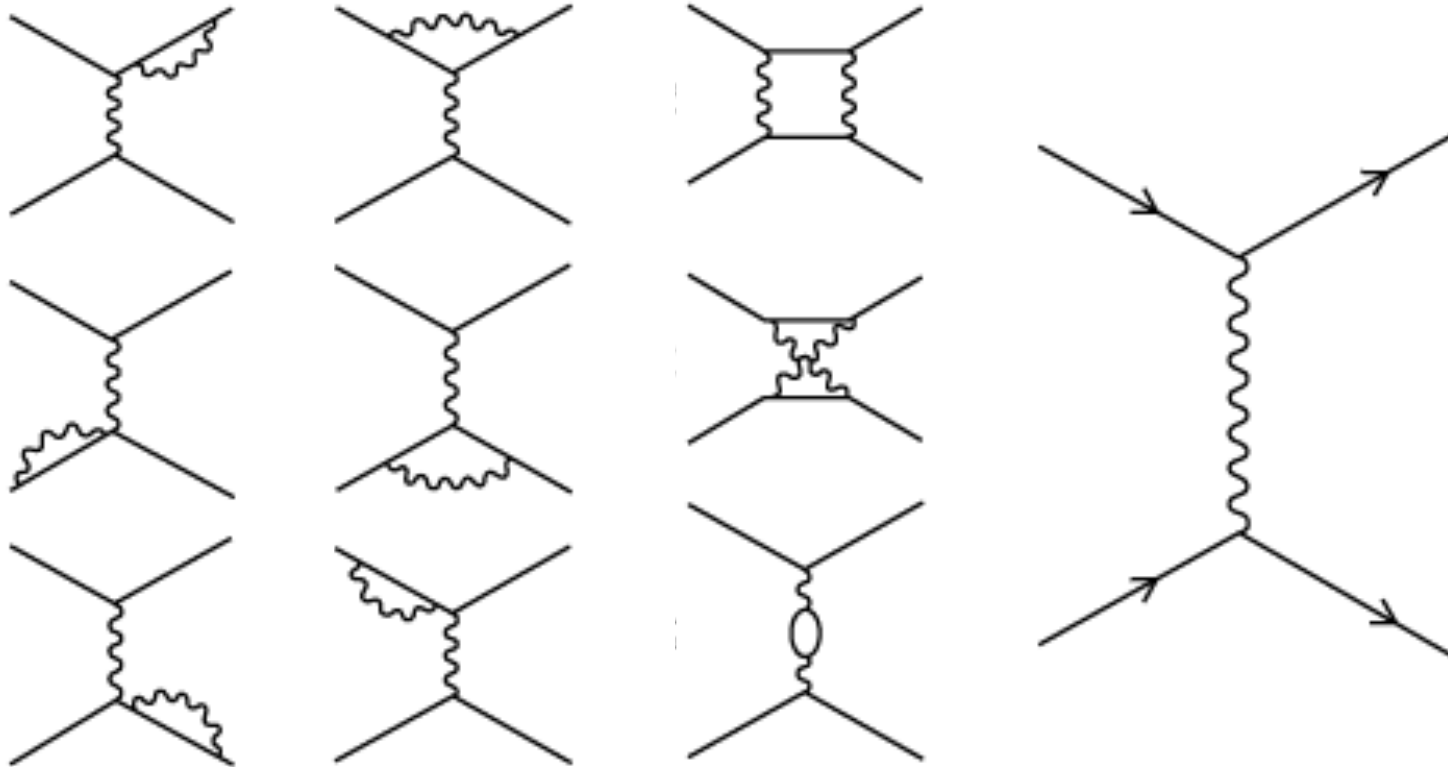












*But not all theories yield sensible answers
to these kinds of calculations*



Summit: 29,028 ft



Sea Level: 0 ft

Summit: 29,028 ft



Summit: 11,328 ft

Base Camp: 0 ft

Sea Level: 0 ft

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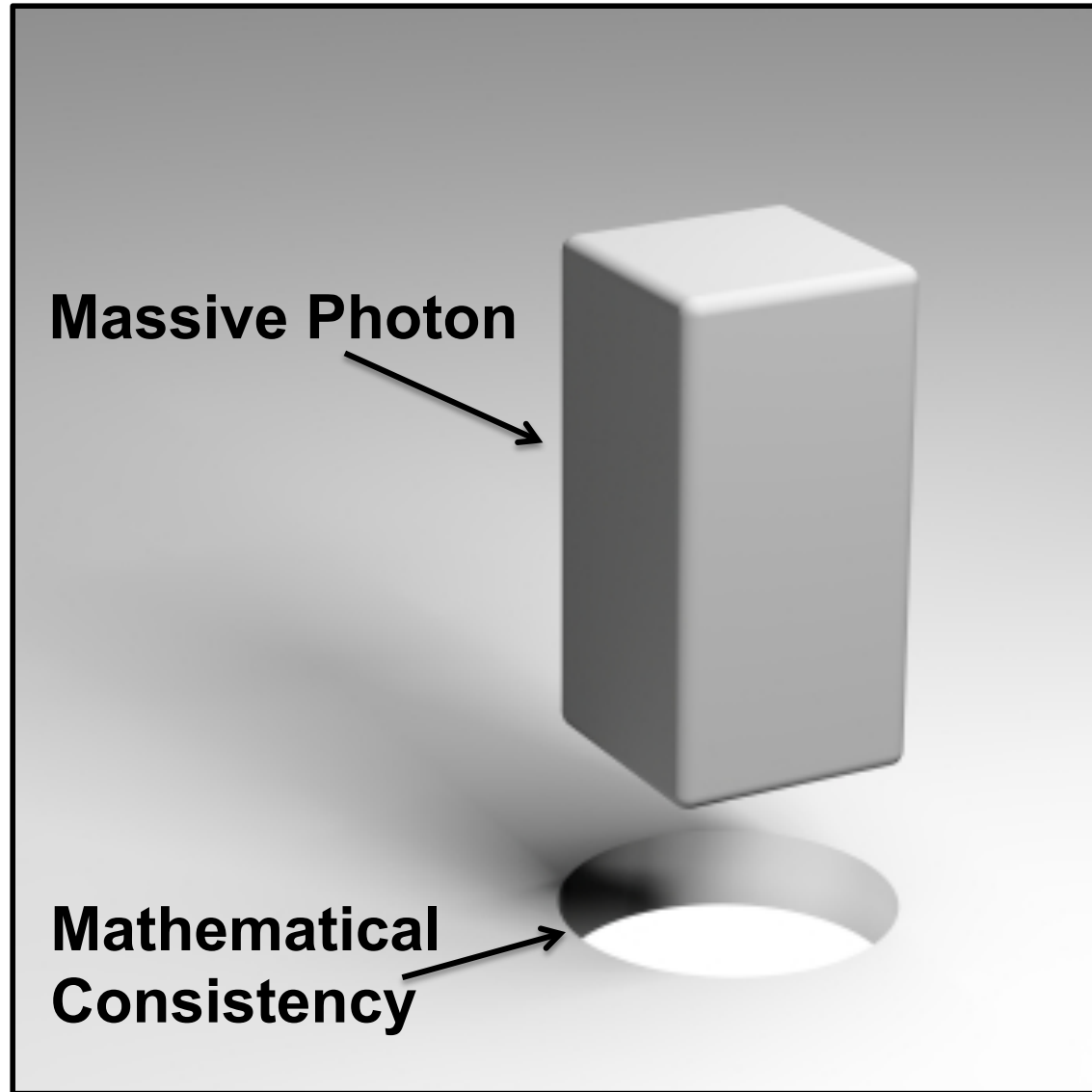
Sea Level: 0 ft

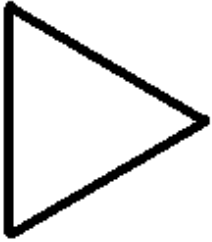
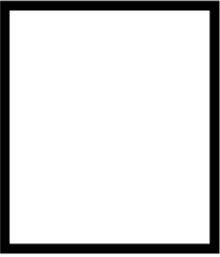
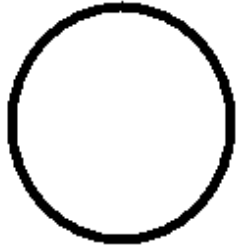
In order for Quantum Theory to produce the same answers when calculating in different gauges, the photon must be exactly massless

Massive Photon



**Mathematical
Consistency**





Conservation of:

Symmetry of:

Energy \longleftrightarrow Time

Momentum \longleftrightarrow Space

Angular Momentum \longleftrightarrow Rotation

Conservation of:

Symmetry of:

Energy \longleftrightarrow Time

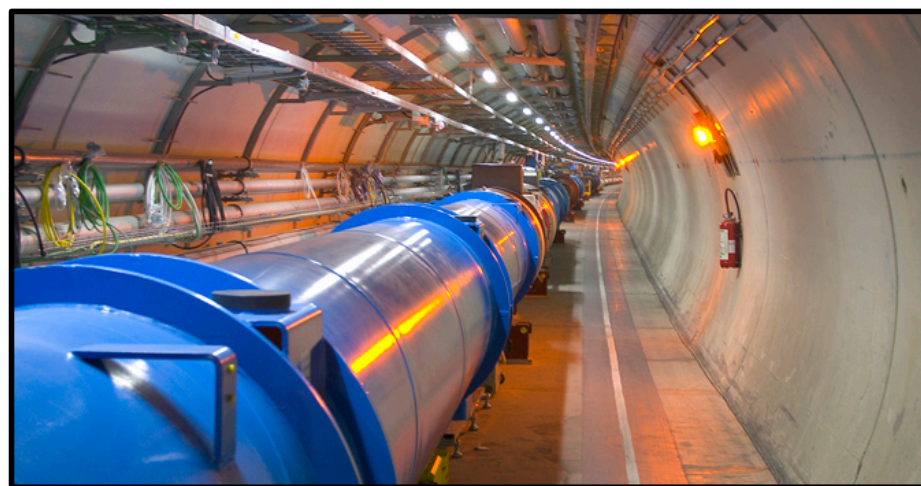
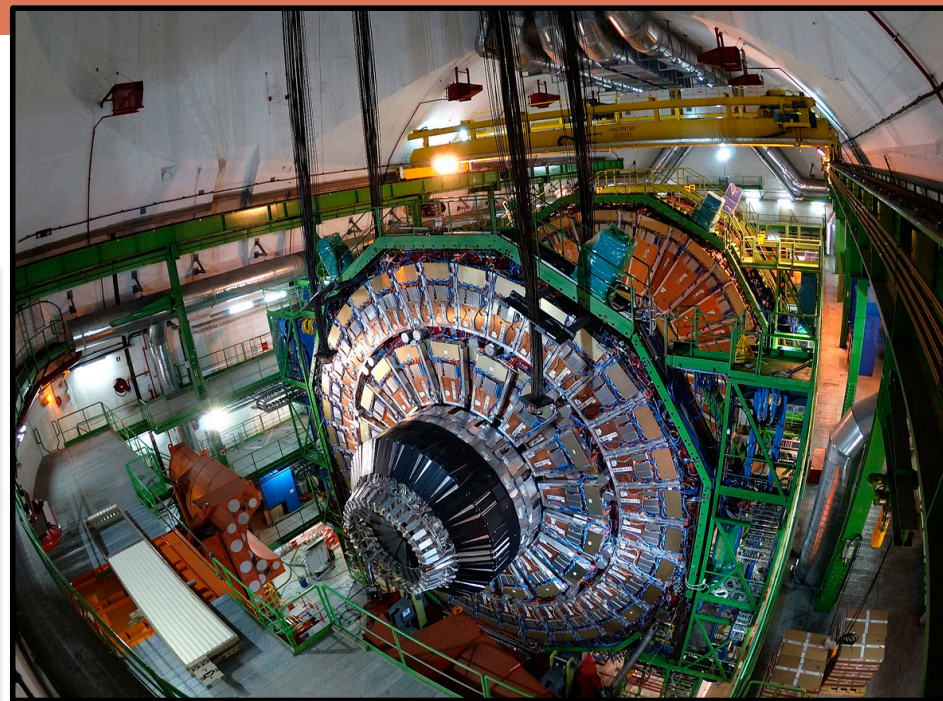
Momentum \longleftrightarrow Space

Angular Momentum \longleftrightarrow Rotation

Electric Charge \longleftrightarrow Gauge Transformation



$SU(3) \times SU(2) \times U(1)$

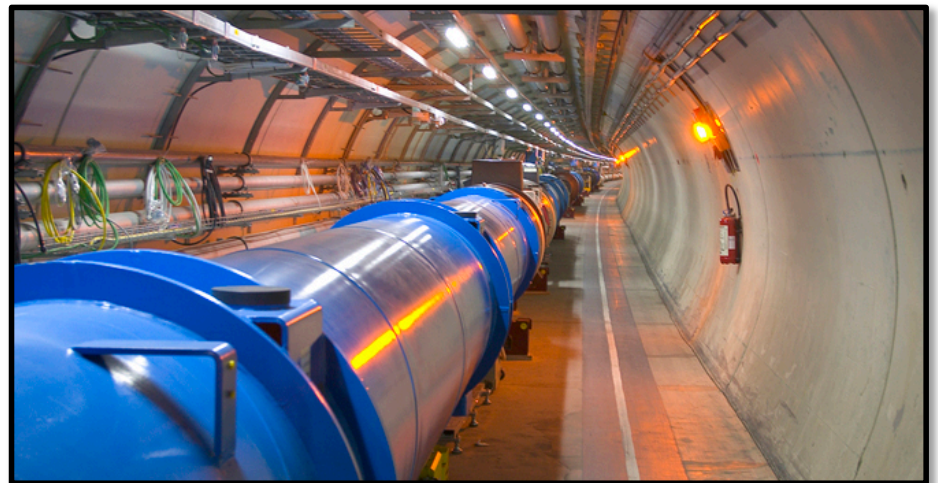




17 mile circumference
tunnel, up to 570 feet
beneath the city of Geneva
and nearby France



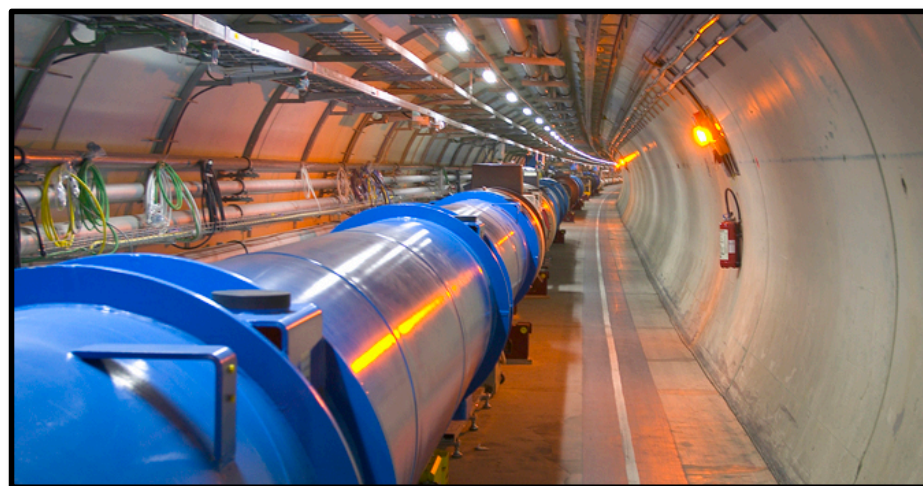
Using powerful magnets, beams of protons are accelerated in each direction around the tunnel, until they are traveling at 99.999997% of the speed of light

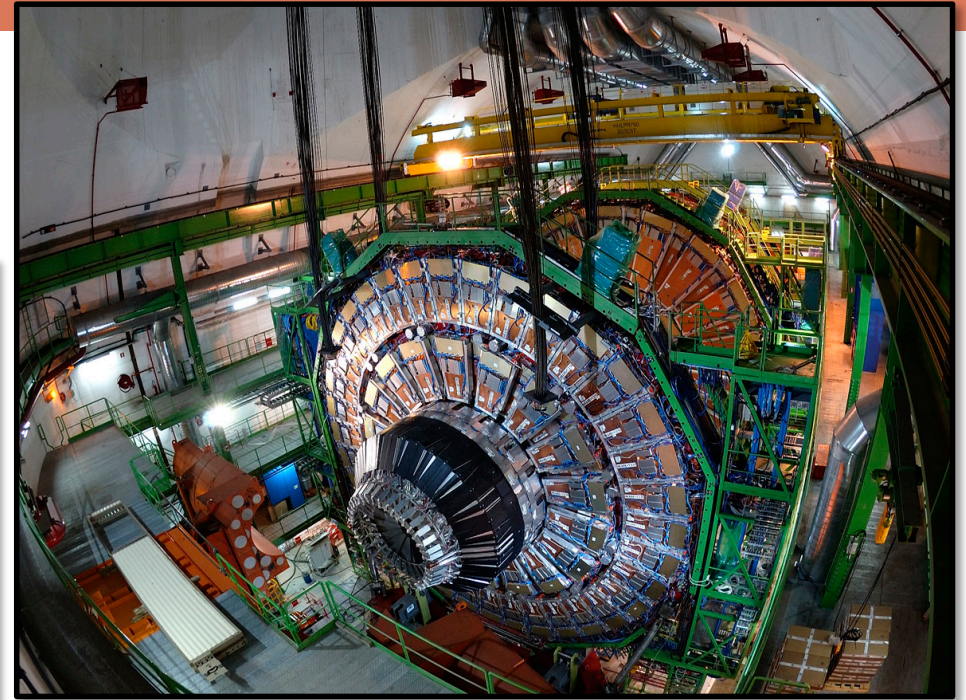




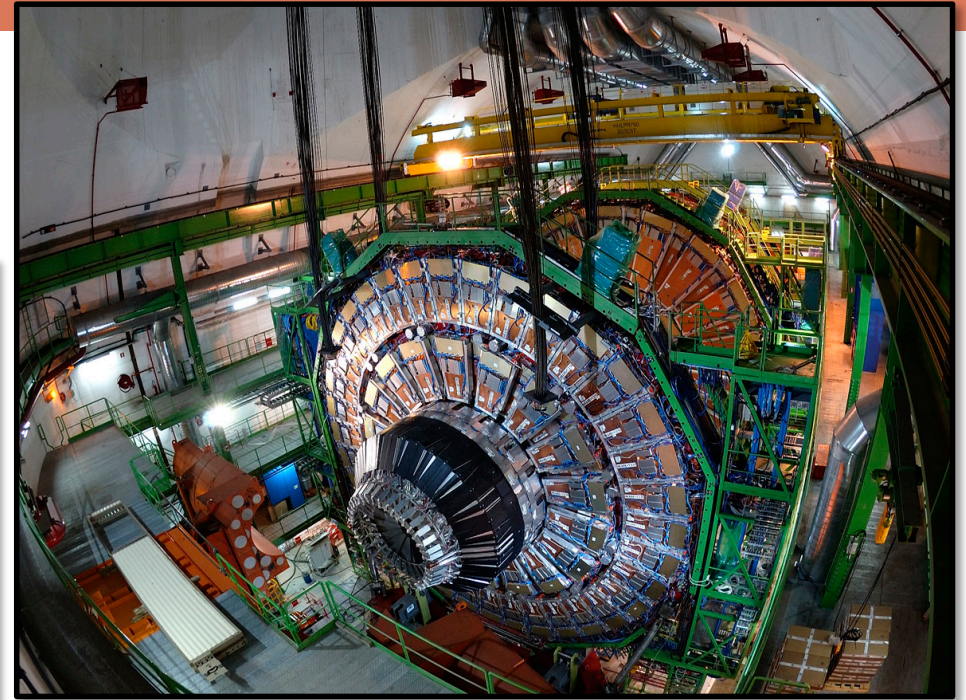
Using powerful magnets, beams of protons are accelerated in each direction around the tunnel, until they are traveling at 99.999997% of the speed of light

These protons make about 11,000 revolutions around the ring each second



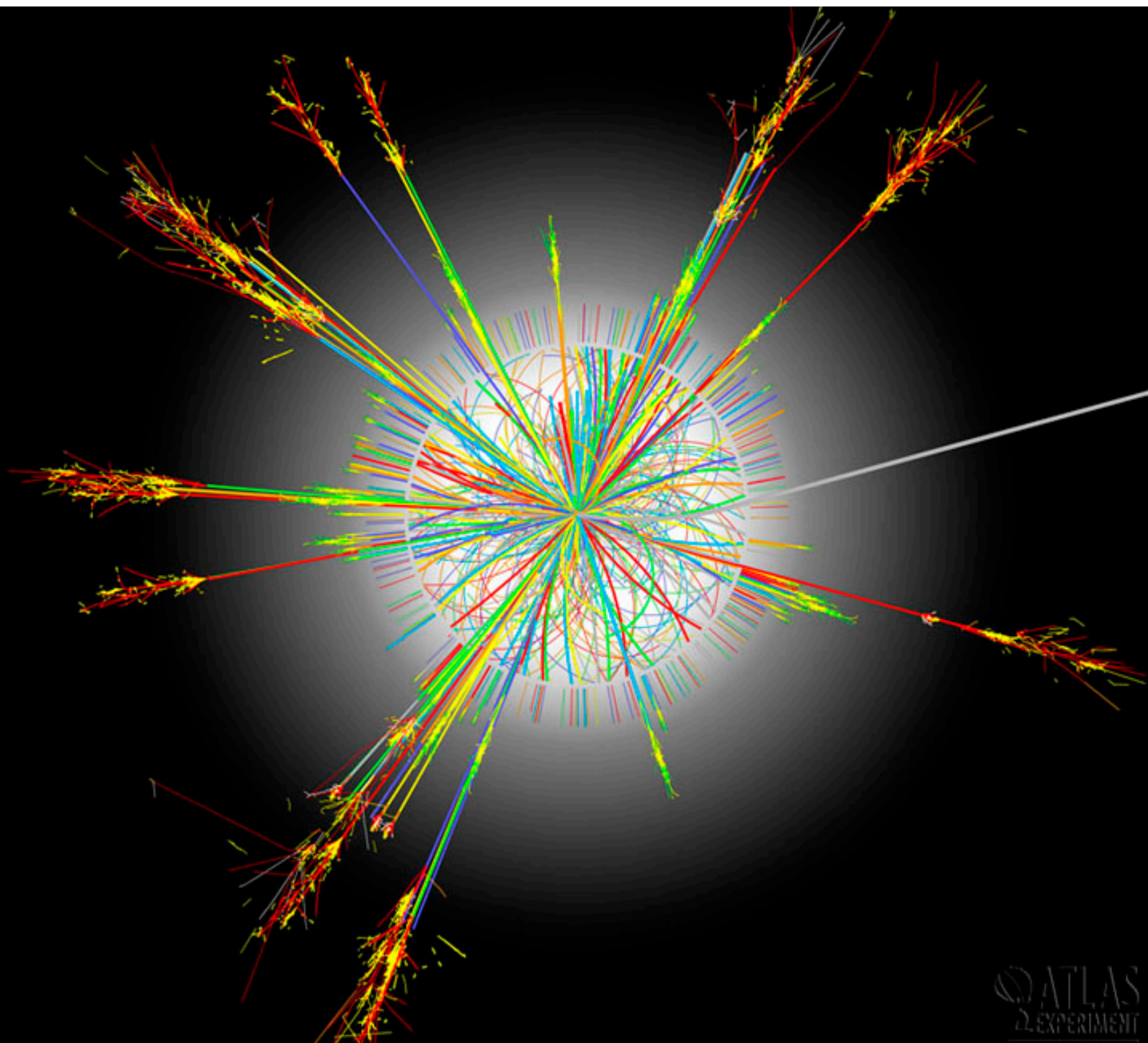


The proton beams are collided head-on into each other inside of enormous detectors, which measure the resulting explosion of particles



The proton beams are collided head-on into each other inside of enormous detectors, which measure the resulting explosion of particles

The LHC produces and observes roughly 100,000,000 collisions per second



ATLAS
EXPERIMENT

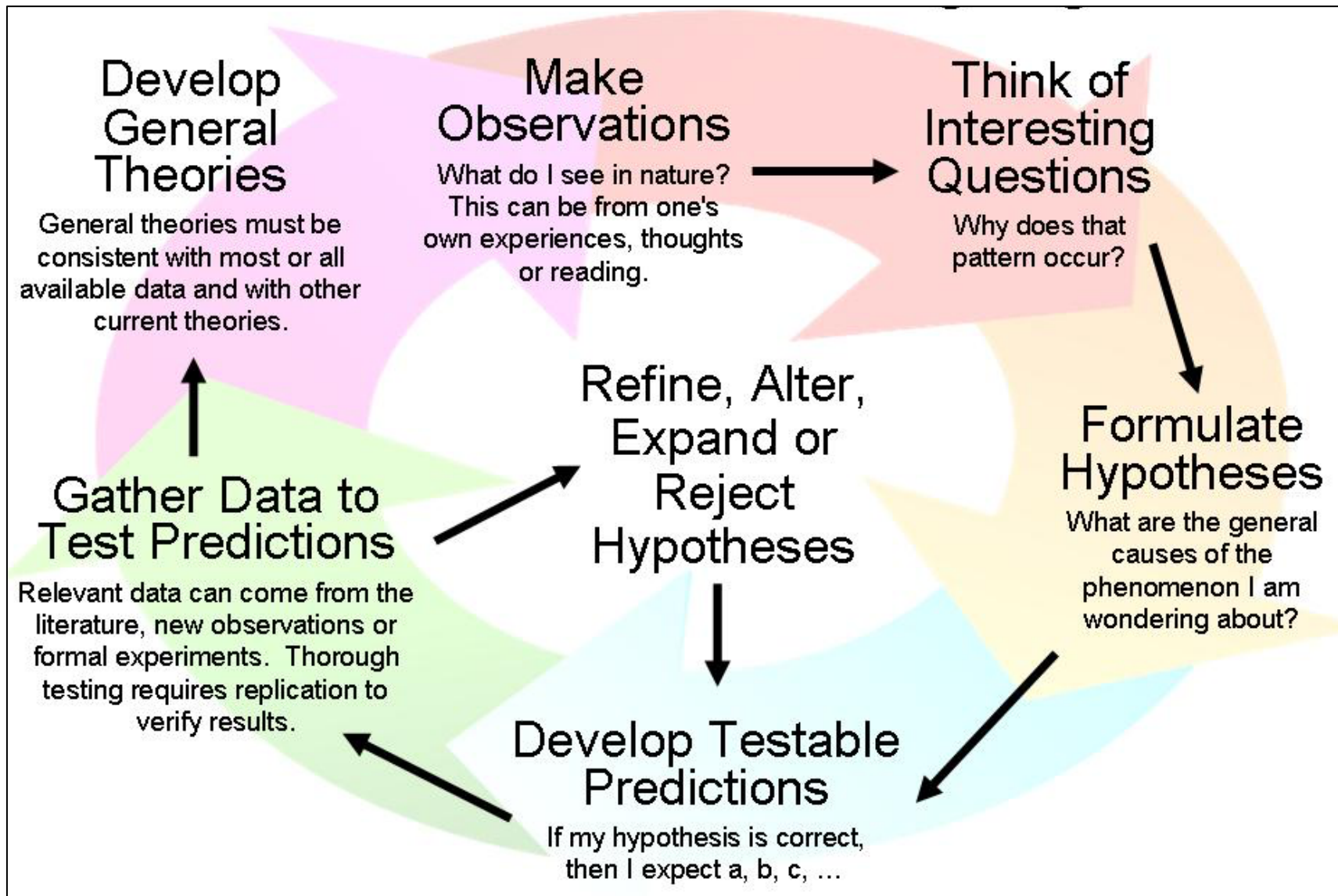
Some of the Ongoing Experiments At Fermilab


- The Cryogenic Dark Matter Search (CDMS)
- The Dark Energy Survey (DES)
- The Deep Underground Neutrino Experiment (DUNE)
- The MiniBooNE and MicroBooNE Neutrino Experiments
- The Main Injector Neutrino Oscillation Search (MINOS)
- Mu2e (muon to electron conversion experiment)
- Muon g-2
- NovA
- And many others...



But what is “Science”?

But what is “Science”?





“If we take in our hand any Volume; of Divinity or School Metaphysics, for Instance; let us ask, Does it contain any abstract Reasoning concerning Quantity or Number? No. Does it contain any experimental Reasoning concerning Matter of Fact and Existence? No. Commit it then to the Flames: For it can contain nothing but Sophistry and Illusion.”

-David Hume

(An Enquiry Concerning Human Understanding, 1748)



“Whereof one cannot speak, thereof one must be silent.”

-Ludwig Wittgenstein
(Tractatus Logico-Philosophicus, 1922)



Are There Alternatives to the Scientific Method?

Are There Alternatives to the Scientific Method?

Reliance on tradition or authority

- This is something of a straw man opponent to science; few would argue that science conducted sufficiently fairly and carefully will often lead to conclusions that are likely to be false
- Many instances of reliance on tradition are actually a weak form of reliance on social science – if many people held position X in the past, then this provides a limited degree of empirical evidence that holding position X is likely to be helpful or advantageous

Are There Alternatives to the Scientific Method?

Reliance on tradition or authority

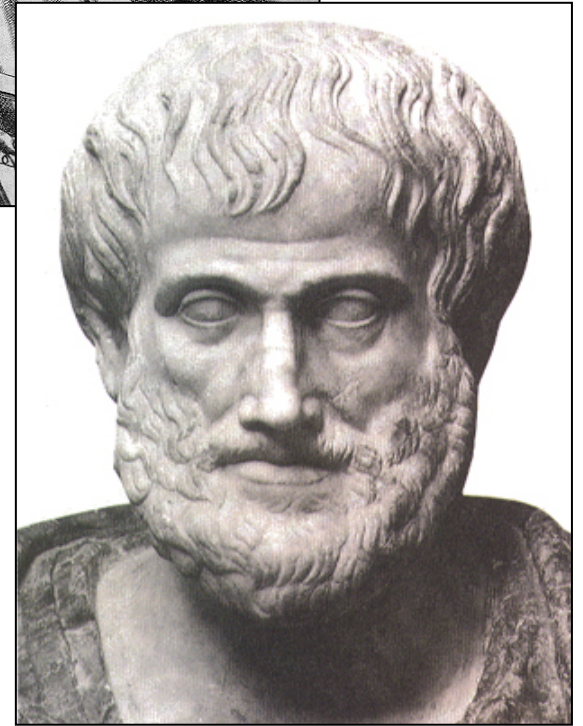
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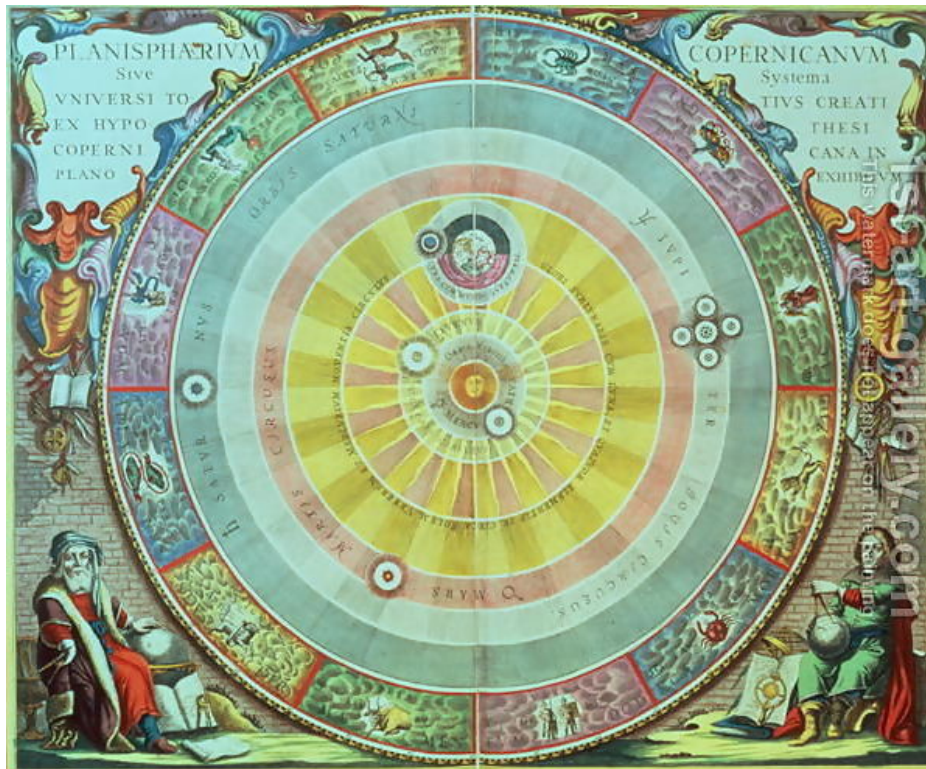
Reliance on pure reasoning (mathematics, philosophy)

- Many people think of mathematics as a part of science, but it is fundamentally not grounded in empiricism (a central part of the scientific method)
- Although philosophers of science hold a range of opinions on this issue, my view is that math helps to illuminate the relationships between ideas and can help to clarify our thinking, but does not itself tell us anything about our world

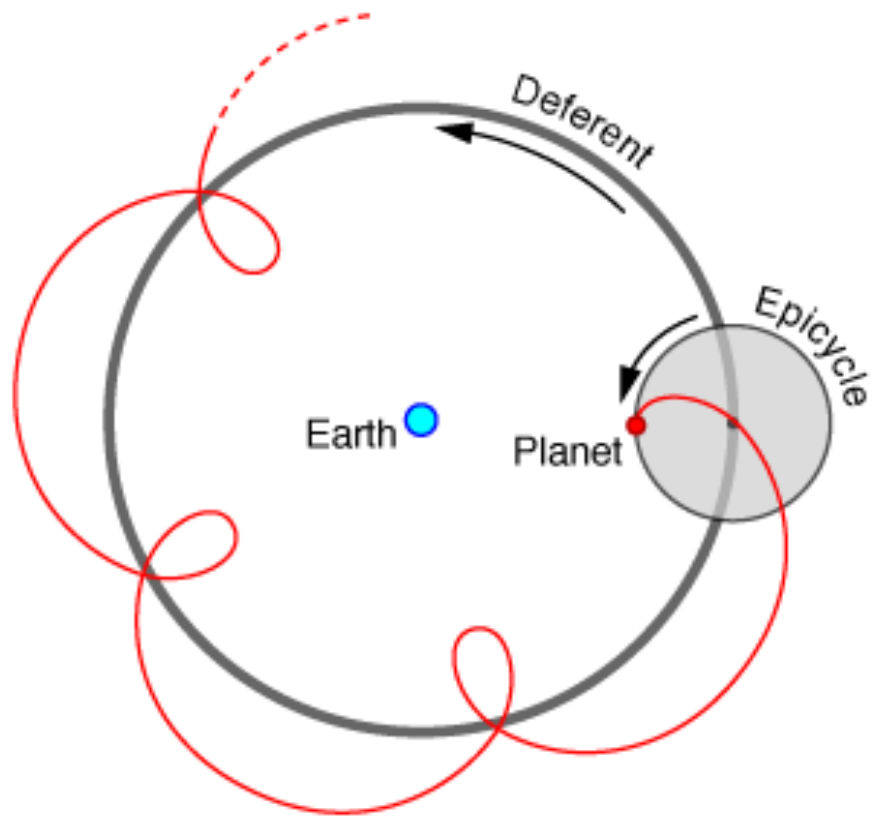


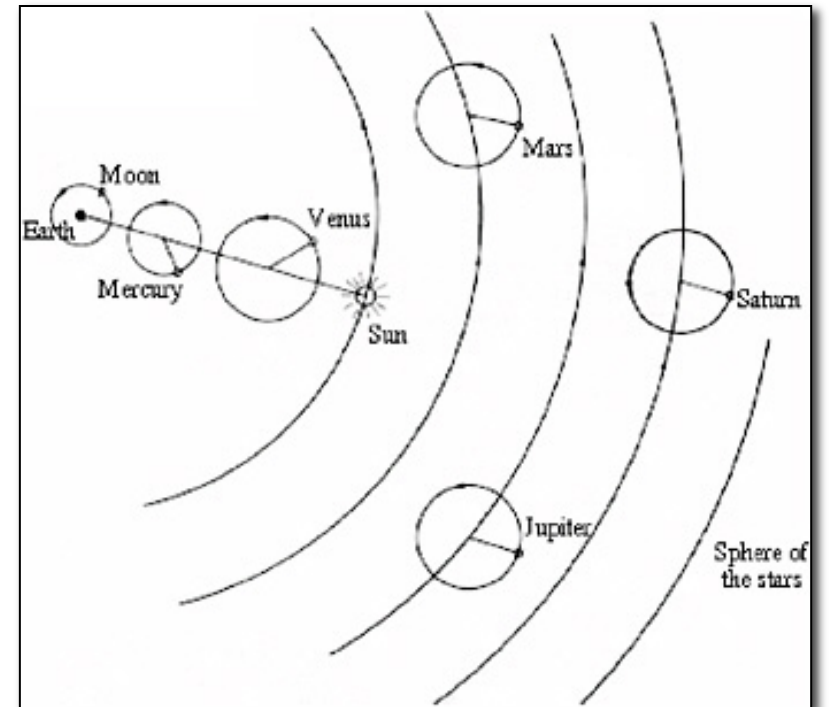
VS

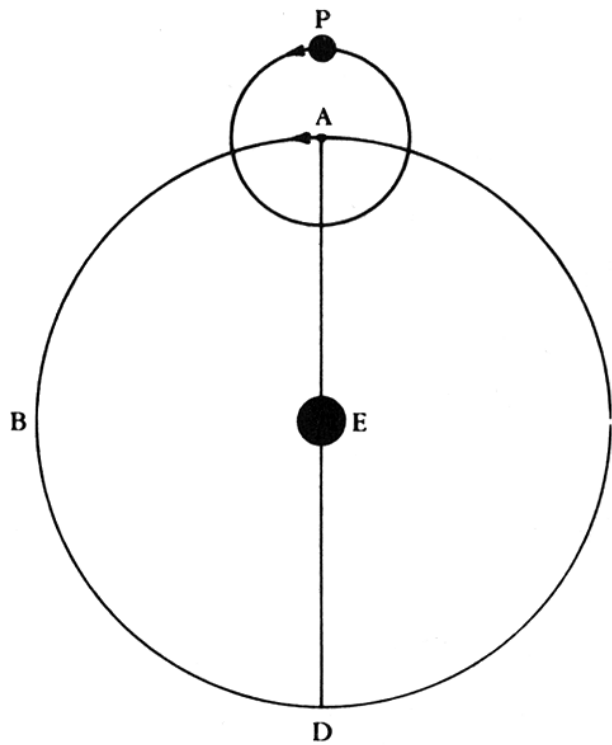




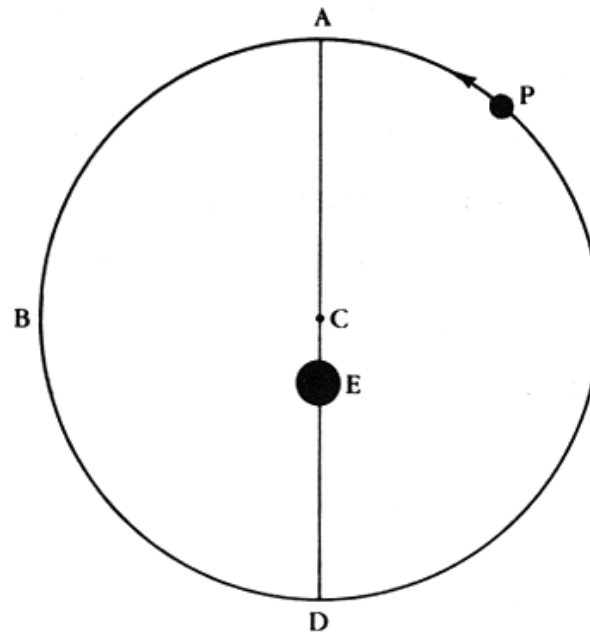




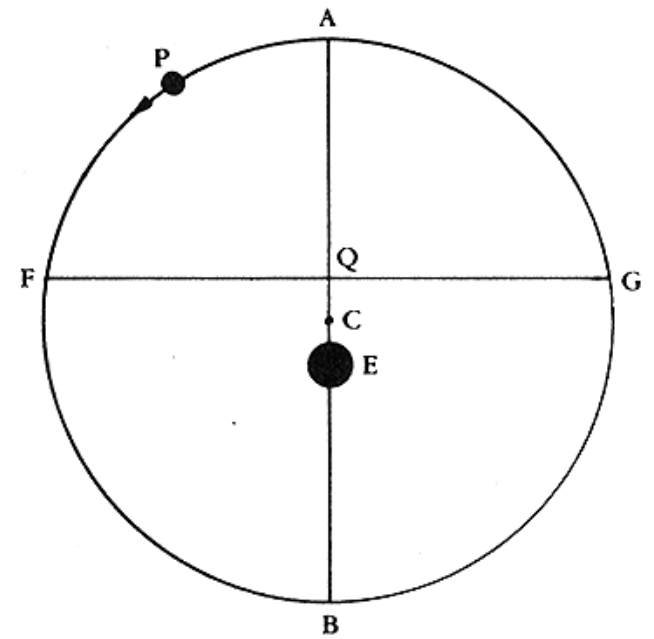




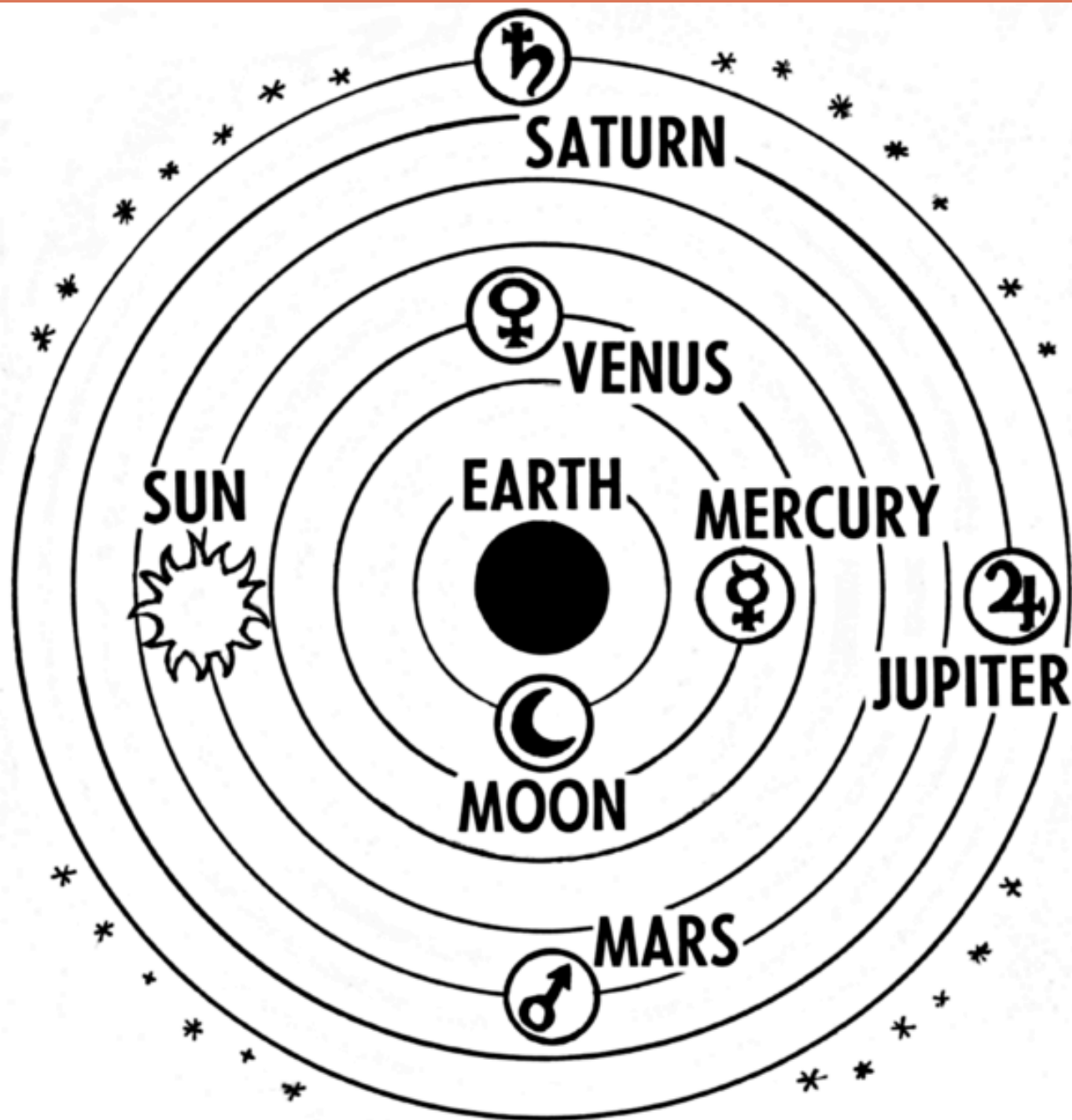
Epicycle

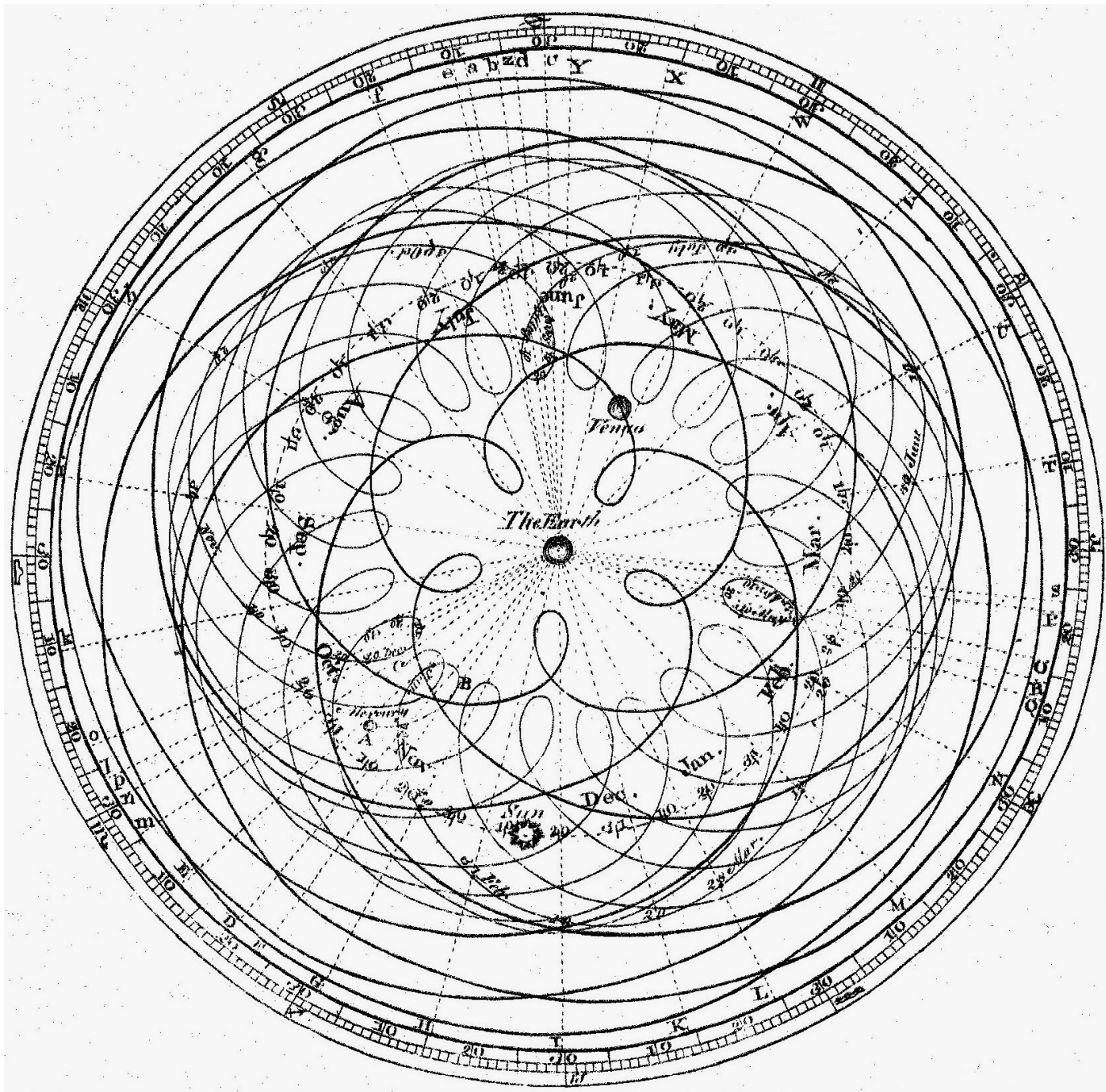


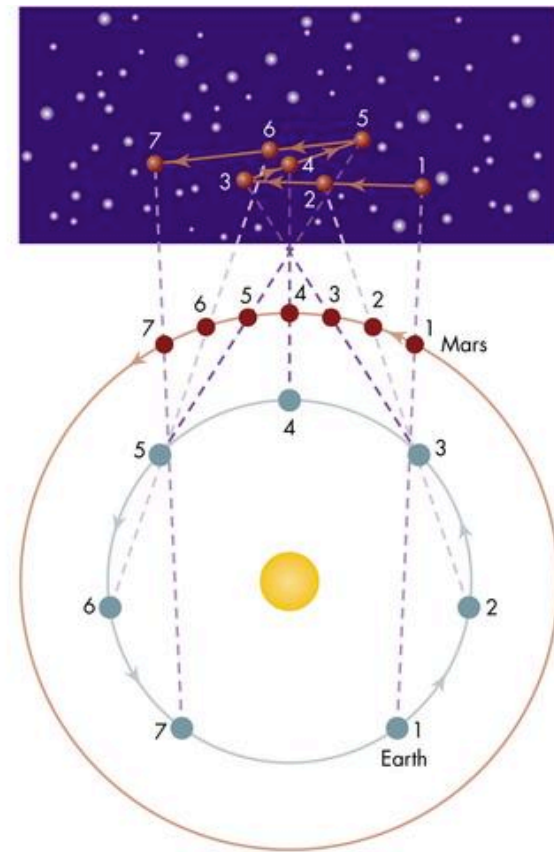
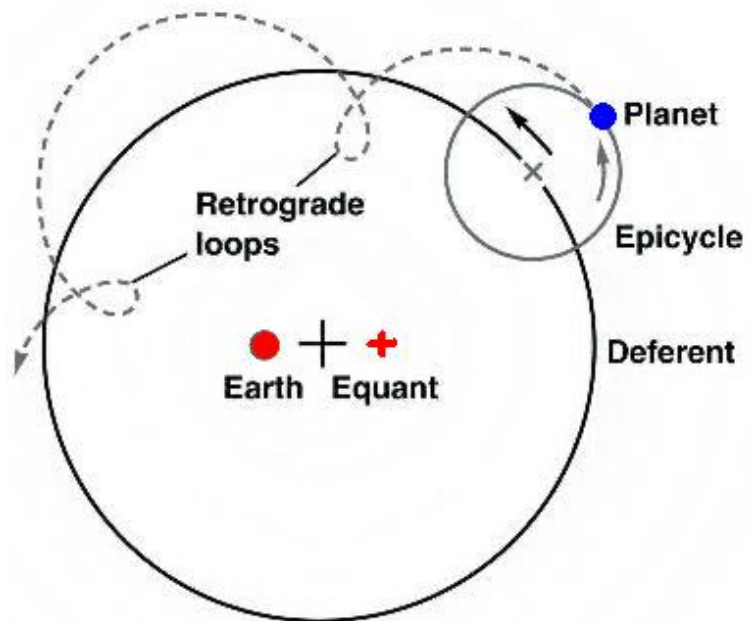
Eccentric



Equant

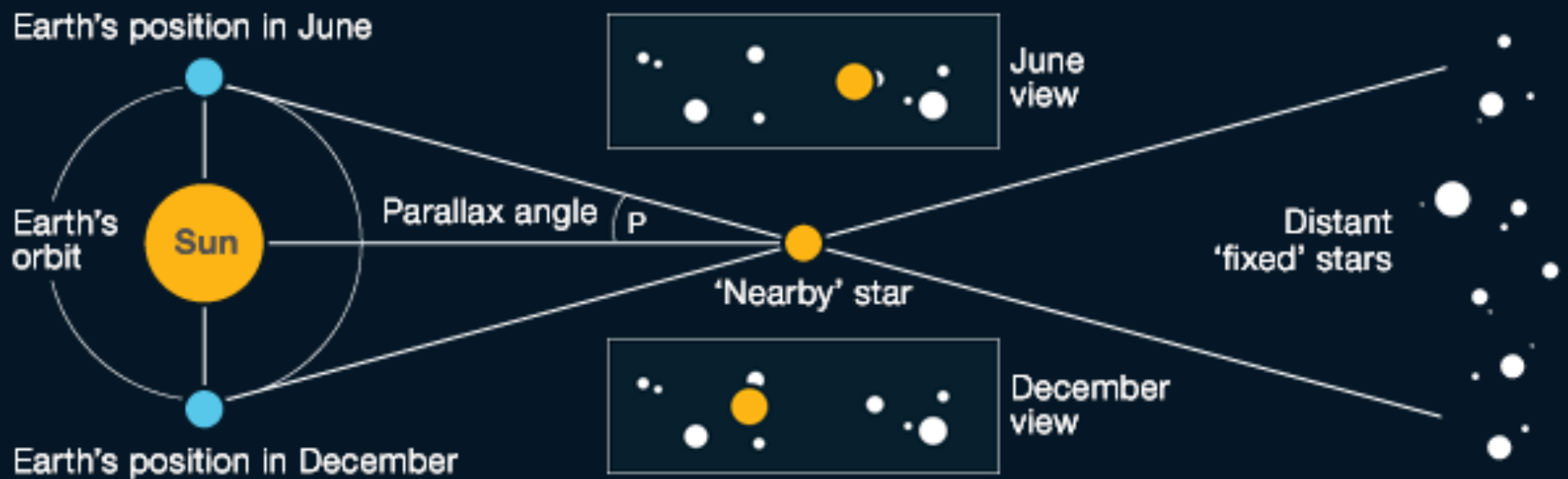








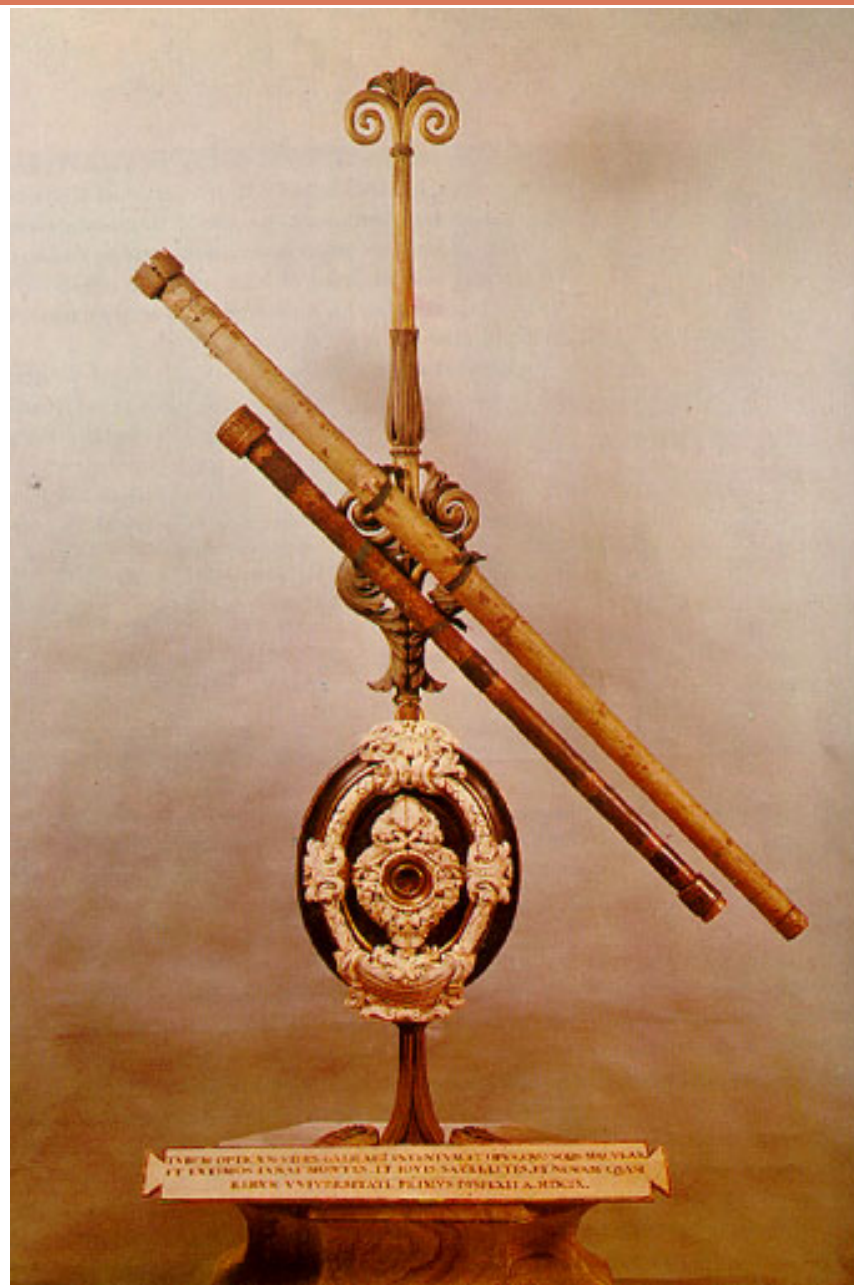
Stellar parallax: Measuring the distance of stars



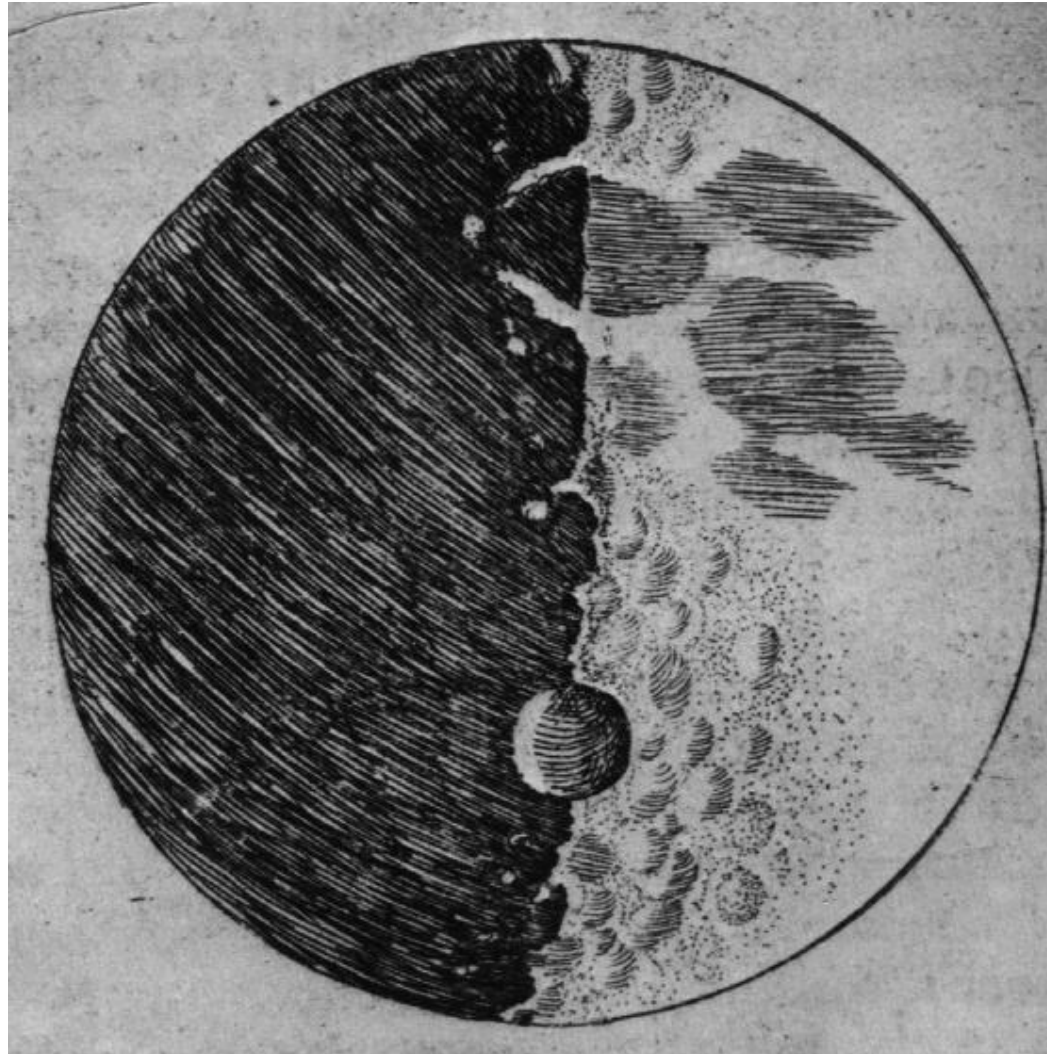
Source: University of Virginia

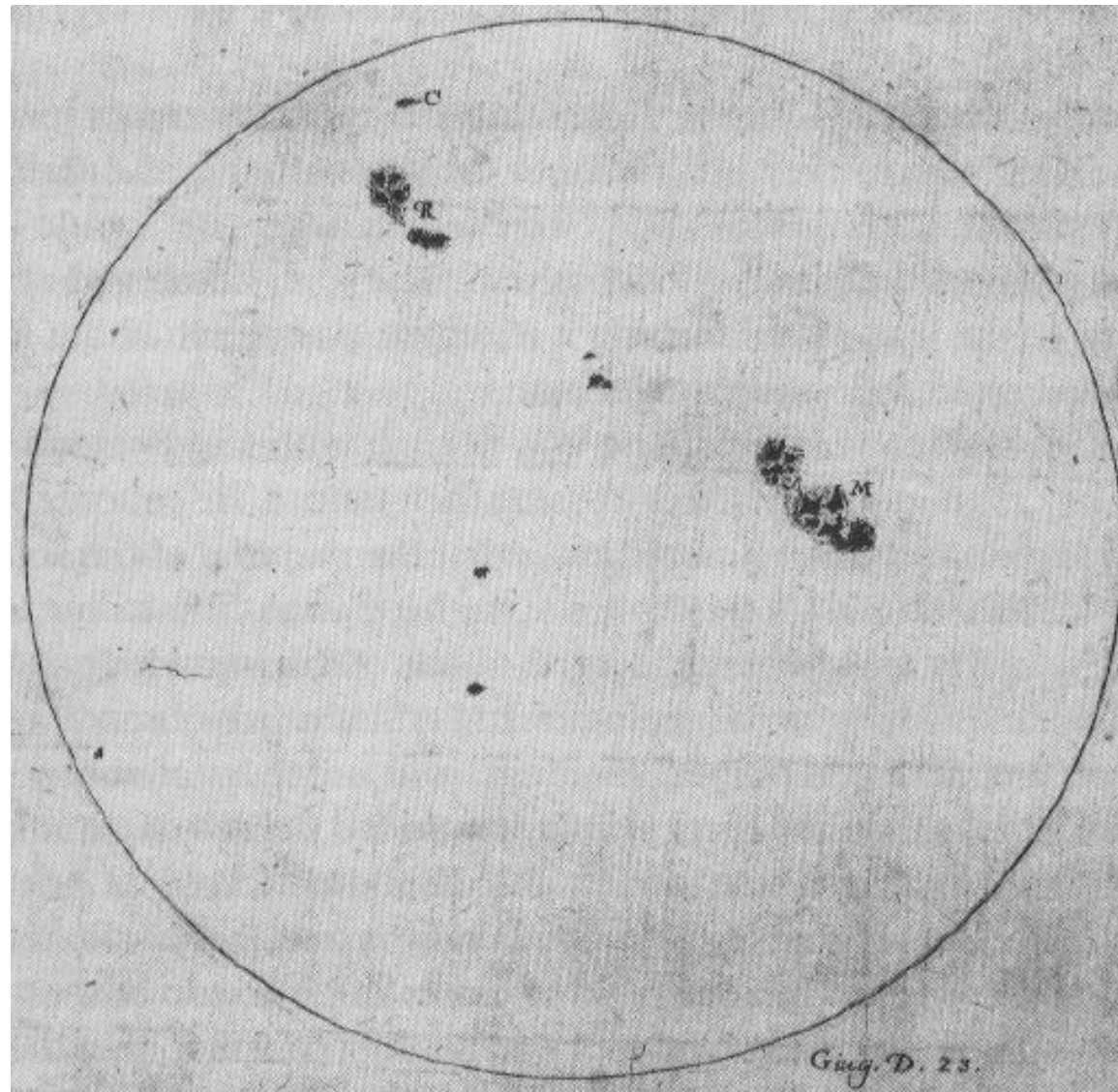




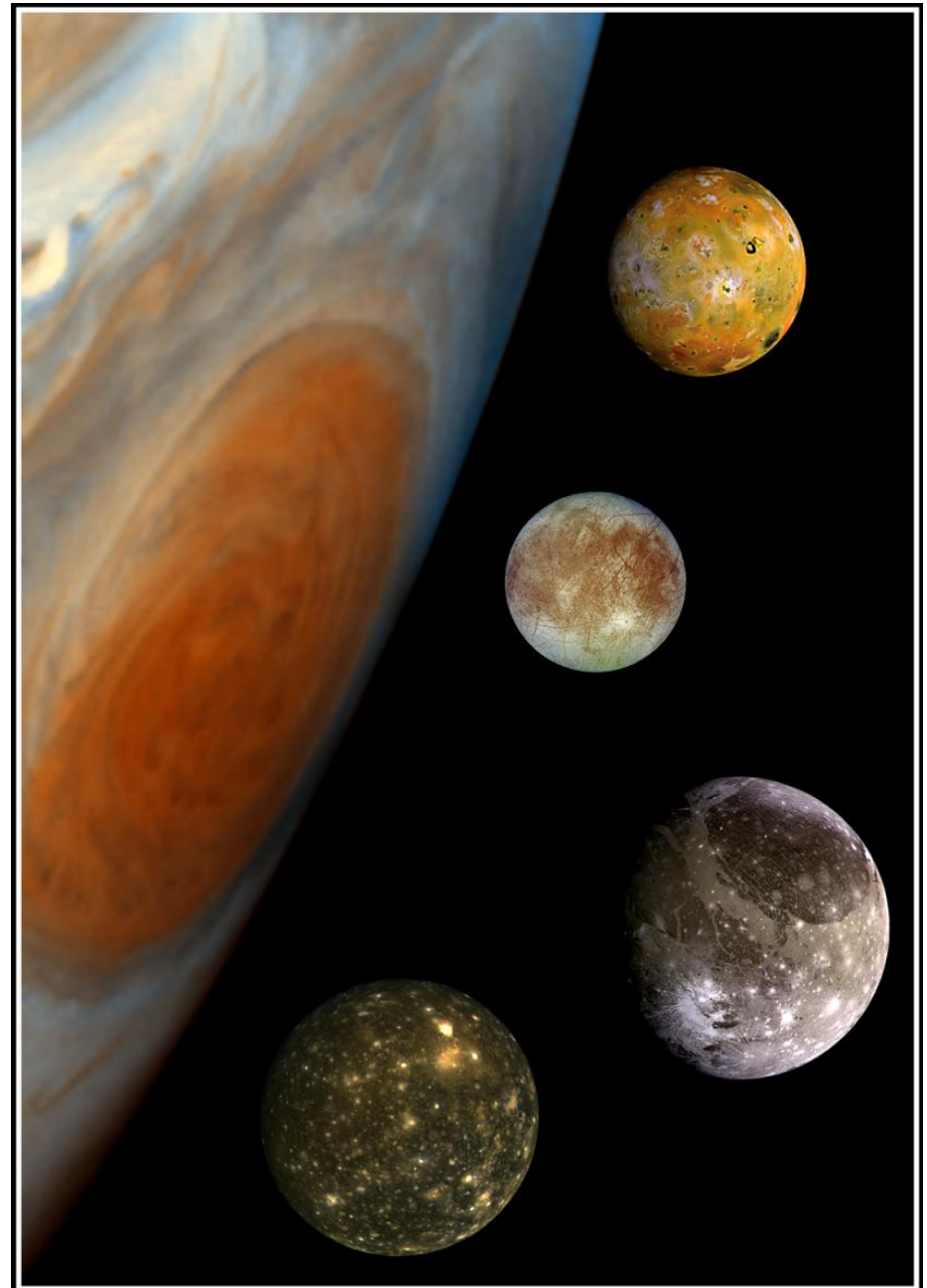


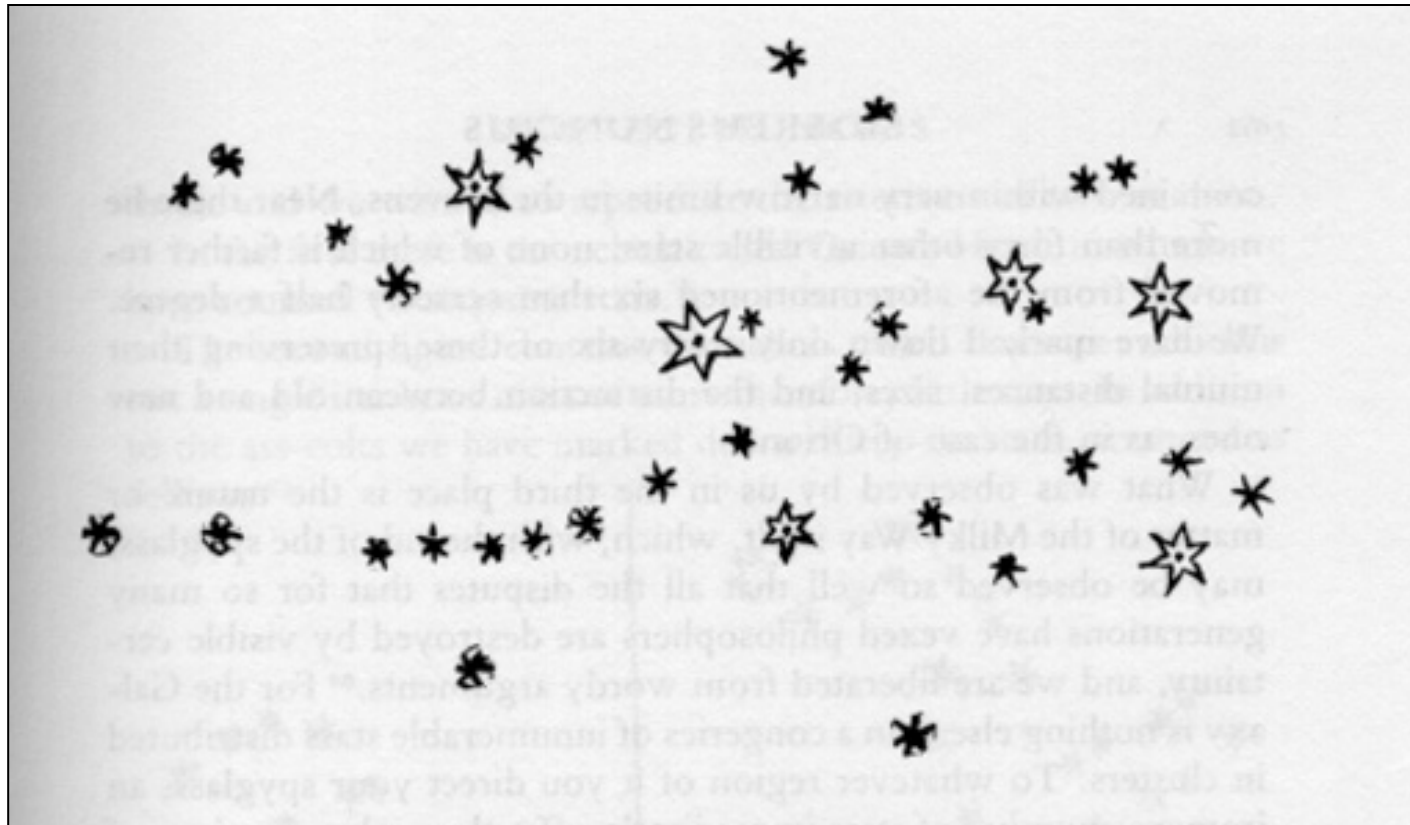
IN HOC OPTICUS VIDEI GALLIARDI ANTIQVARI ET OPTICUS SORDI MONTAN
ET EXIMIO LARAI MONTAN. ET HUIUS SACRILEGII ET INQVAM QVAM
RIDER ANTIQVARI ET INQVAM QVAM RIDER.

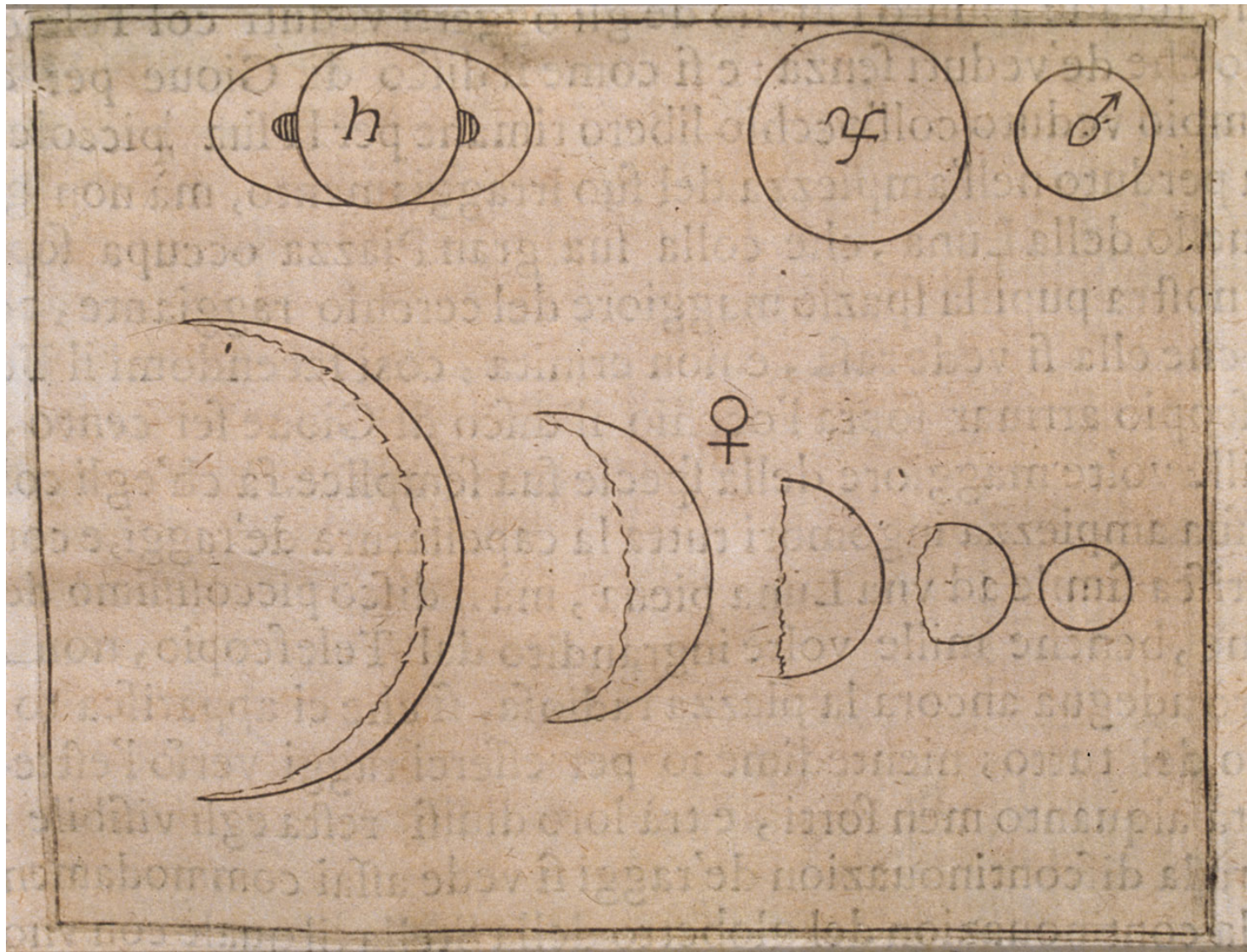


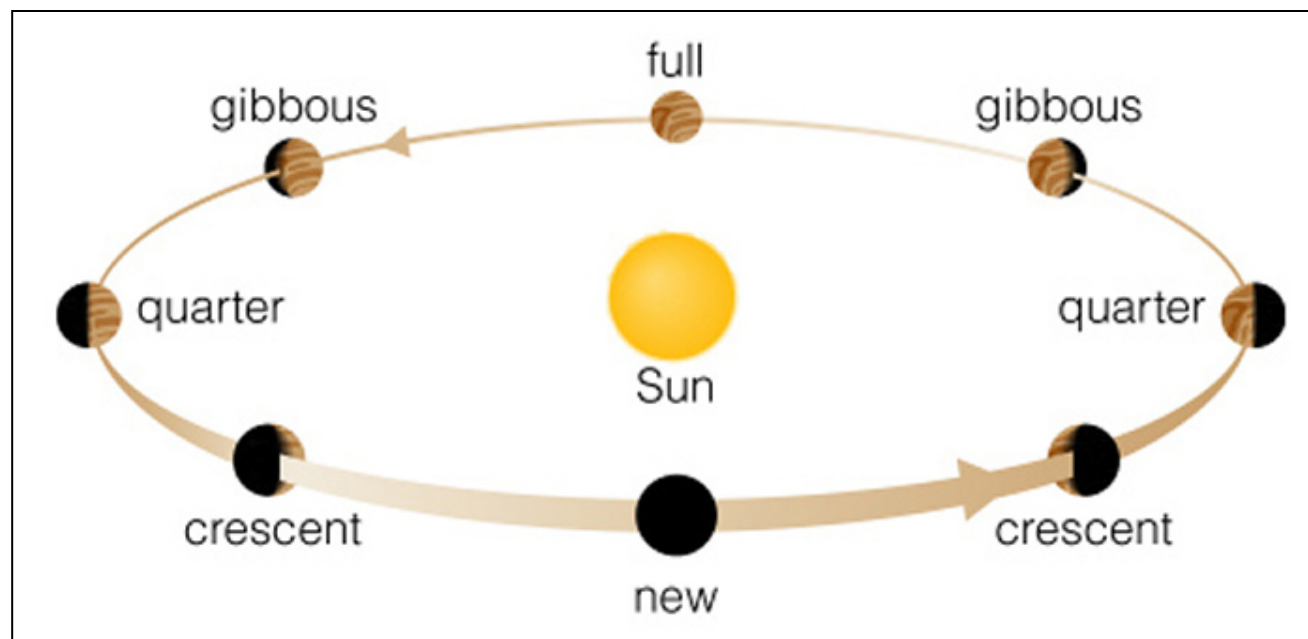
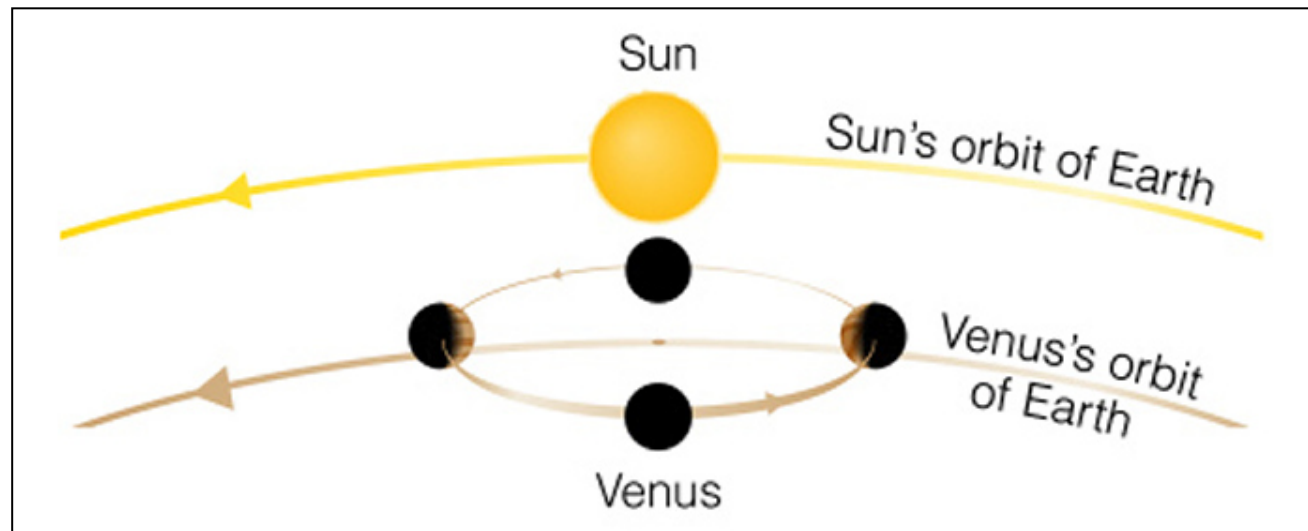


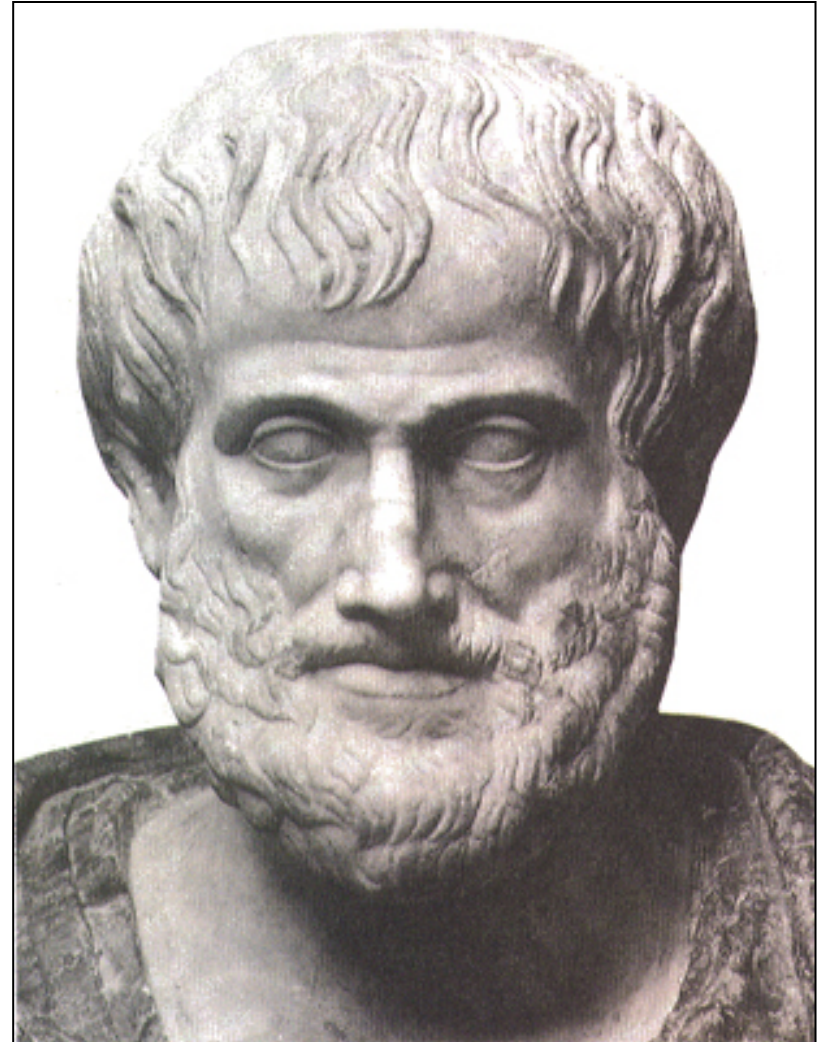
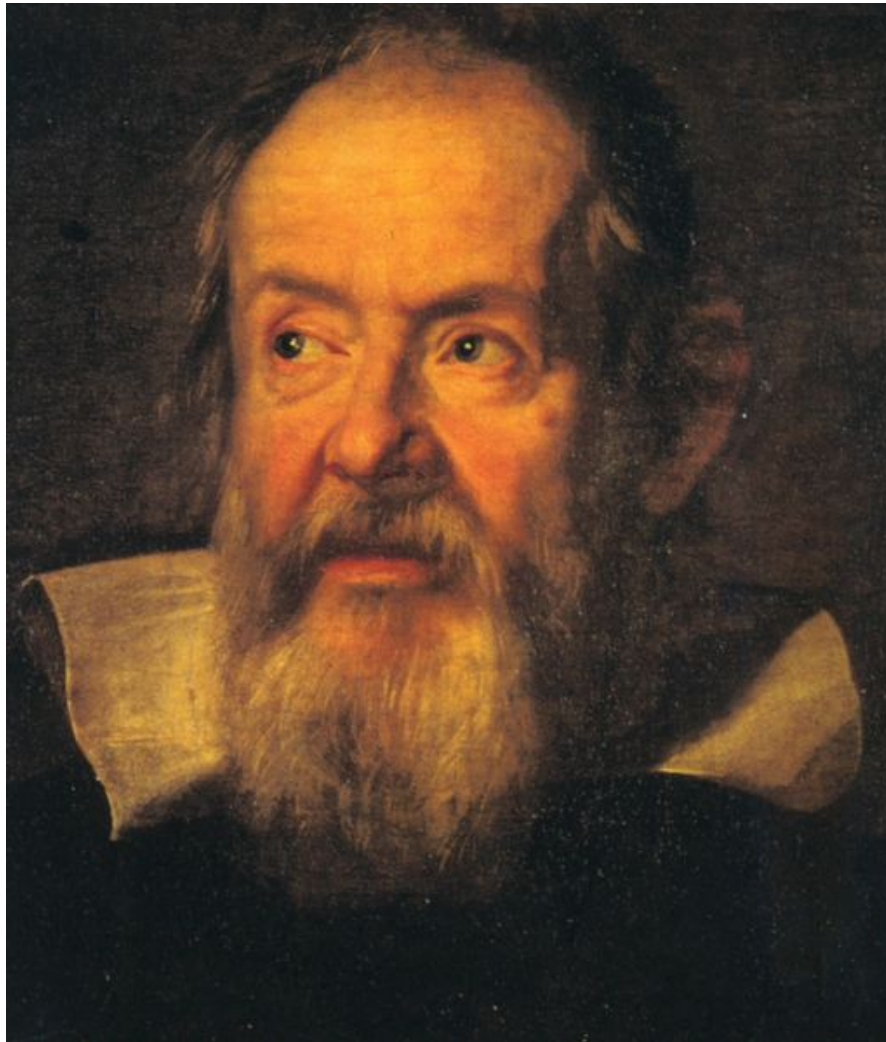
Observations Jovianae				
2. J. Jovianae				
man H. 12	○	*	*	
30. man	*	*	○	*
2. Jovianae	○	*	*	*
3. man	○	*	*	
3. Ho. 5.	*	○	*	
4. man	*	○	*	*
6. man	*	*	○	*
8. man H. 13.	*	*	*	○
10. man	*	*	*	○
11.	*	*	○	*
12. H. 4. Jovianae	*		○	*
13. man	*	*	○	*
14. Jovianae	*	*	○	*

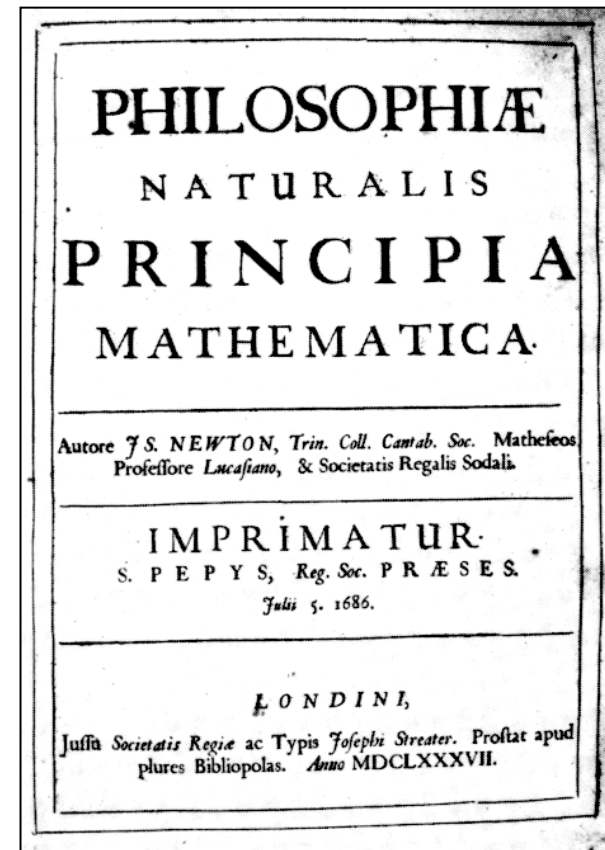
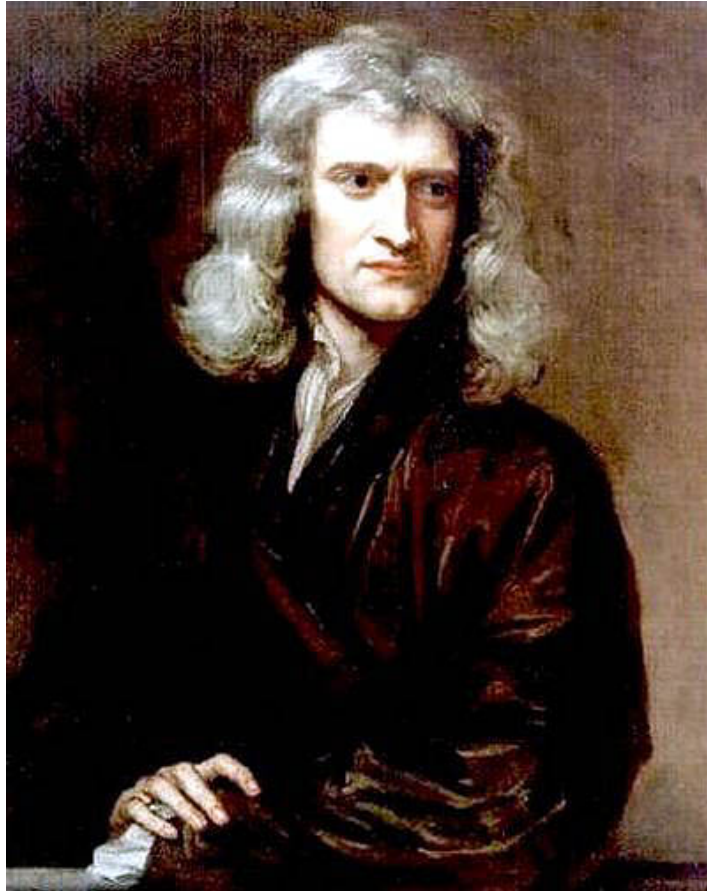








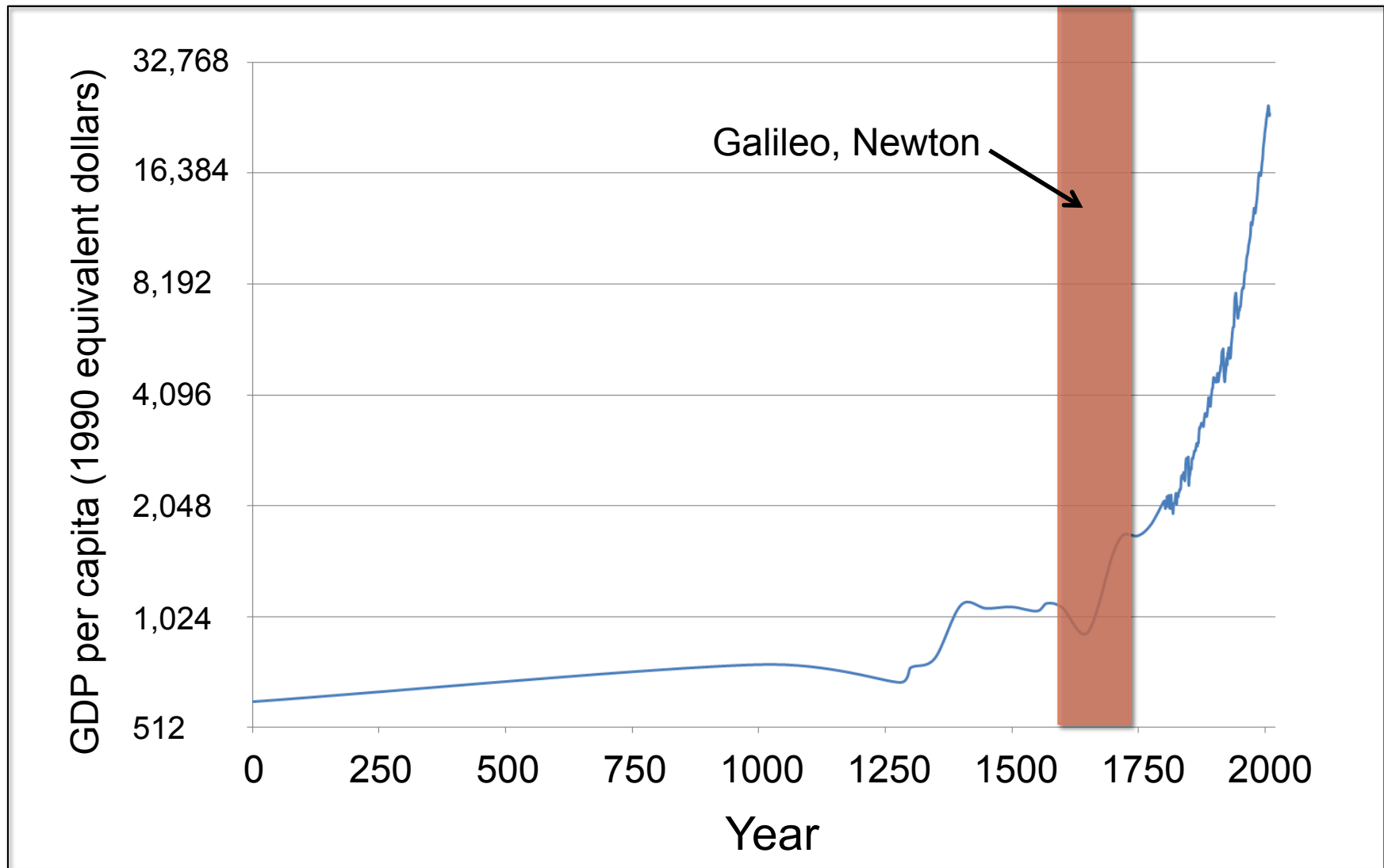




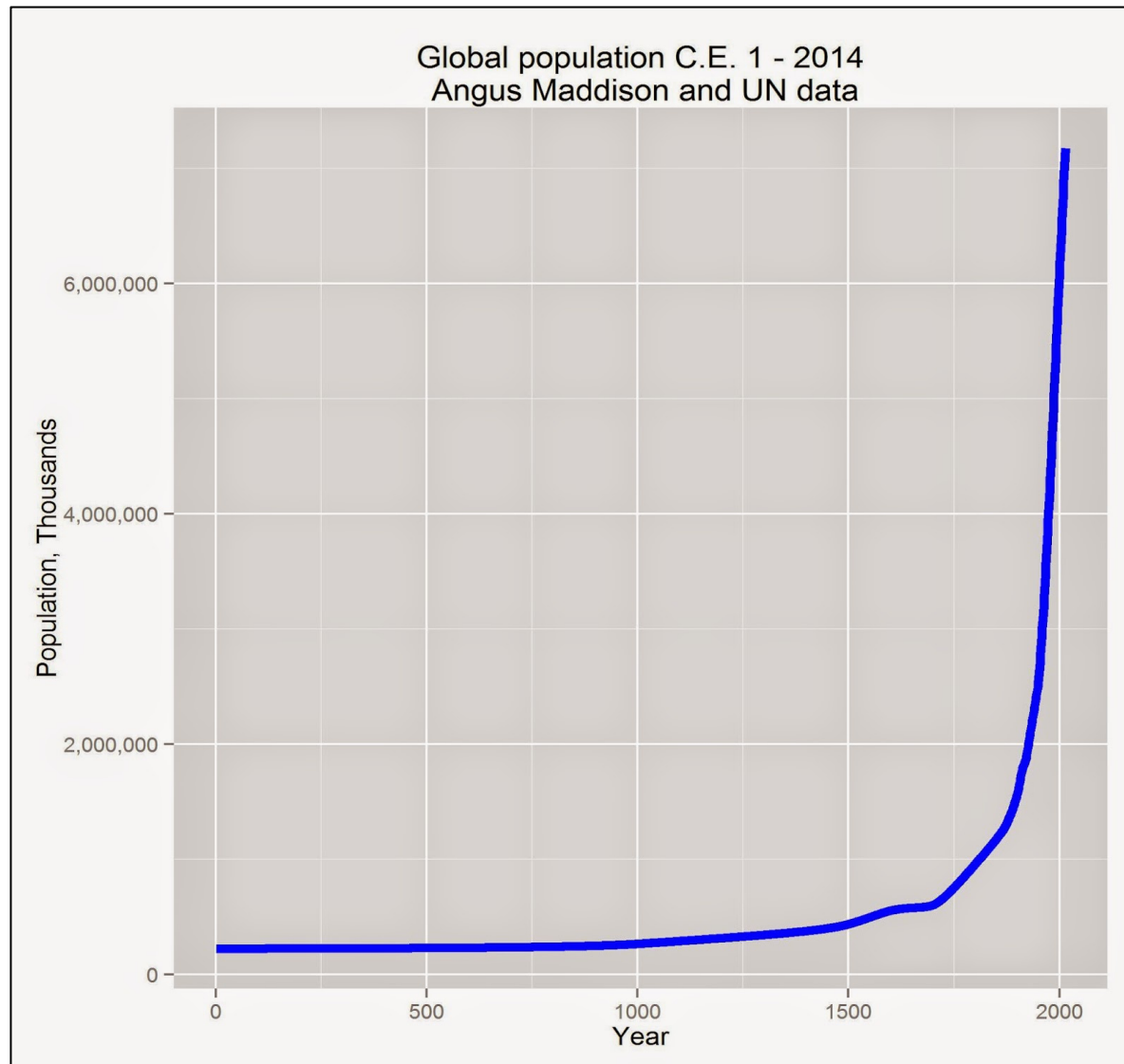


Why Is Science Important?

Why Is Science Important?



Why Is Science Important?



Why Is Science Important?

- Ultimately, *all* human progress comes from innovation and discovery
- Science (broadly defined) represents our best systematized effort to learn about and understand our world, maximizing the rate of innovation and discovery
- Successful implementation of the scientific method allows us to better control our world, enabling us to improve our lives
- A scientific approach can (and should!) be implemented within every facet of our lives in which we hope to make progress

